Near Real-Time Multi-Sensor Fusion for Cued Reconnaissance

Operational Analysis of Operation Driftnet 2009

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Abstract

In September 2009, Joint Task Force (Pacific) (JTFP) Operational Research (OR) Team was asked to provide analytical support to JTFP J3 Air operations during Operation Driftnet 2009 in order to enhance the effective conduct of operations. This support produced decision aids to allow effective and valid use of RADARSAT-2 (RS2) ship length data for aircraft cuing, and enhanced the amount of relevant data available from Automatic Identification System (AIS) contacts. Based on this experience, several improvements to the processes for sensor data processing and aircraft cuing have been identified.

Résumé

En septembre 2009, l'équipe de recherche opérationnelle (RO) de la Force opérationnelle interarmées (Pacifique) (FOIP) a eu pour mandat de fournir un appui analytique aux opérations aériennes du J3 FOIP dans le cadre de l'opération Driftnet 2009 afin d'améliorer la conduite des opérations. Cet appui a contribué à la production d'aides à la décision permettant une utilisation efficace et adéquate des données RADARSAT-2 sur la longueur des navires aux fins d'orientation des aéronefs vers ces derniers, et accru la quantité de données pertinentes pouvant être extraites des signaux émis par le Système d'identification automatique (SIA). À la lumière de cette expérience, plusieurs améliorations possibles, touchant le traitement des données produites par les capteurs et l'orientation des aéronefs, ont été cernées.

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Executive Summary

Near Real-Time Multi-Sensor Fusion for Cued Reconnaissance: Operational Analysis of Operation Driftnet 2009

S.A. Horn, A. Zegers; DRDC CORA TM 2010-252; Defence R&D Canada – CORA; November 2010.

Background: Driftnet fishing is a highly destructive fishing technique which has severe impacts to many species of sea life. The United Nations, in 1991, issued resolution 46/215 which placed a moratorium on large scale driftnet fishing in international waters. Enforcement of the resolution is a multinational task supported in the North Pacific by Canada, the United States, Japan, Russia, South Korea, and China. Operation Driftnet is a US-Canada bi-national operation conducted by Department of Fisheries and Oceans (DFO), National Marine Fisheries Service (NMFS), United States Coast Guard (USCG), and the Canadian Forces (CF).

During Operation Driftnet 2009, the CP-140 Aurora Long Range Patrol Aircraft (LRPA) is used to patrol the vast North Pacific to monitor for illegal fishing. The typical base of operations for the CP-140 is the Aleutian Islands, but due to runway maintenance, the 2009 operation was conducted from Hawaii. Having Hawaii as the base of operations placed the aircraft further away from historical driftnet fishing areas, requiring more transit time for the CP-140 to reach the patrol zones, thus reducing the overall time available to patrol, and reducing the size of the patrol areas.

To mitigate the effects from the reduced CP-140 patrol time, the use of remote active and passive sensing was trialled as a method to direct the CP-140 more effectively. Two relatively new capabilities were used: RADARSAT-2 (RS2), which is a satellite providing space-based Synthetic Aperture Radar (SAR); and the CanX-6 Nanosatellite Tracking of Ships (NTS) Automatic Identification System (AIS) satellite from COM DEV, which provides space-based detection of AIS transmissions. Combining the information from these two very different sensors, which give very different information up to 8 hours apart, is a very challenging task, but not impossible.

Principal Results: Joint Task Force (Pacific) (JTFP) Operational Research (OR) was able to correlate these two sensors, and provide some analysis on their capabilities and characteristics. Two key capabilities were demonstrated: Near Real Time (NRT) fusion, and static operational decision aids. These two capabilities were demonstrated to have utility in generating Targets of Interest (TOIs), which could then be passed to the CP-140 for intercept.

The principal outcomes are:

1. A methodology for sensor and data fusion was developed and implemented.
2. The fusion results and static decision aids were used to identify TOIs for cuing reconnaissance flights.
3. An operational process to use remote sensing for cuing a patrol aircraft before, and during patrols was developed and shown to be feasible.

The sensor and data fusion results generated an important data set of measurements of variance between the sensors. These measurements were then exploited to support the decision making process. A novel and innovative technique from experimental neuroscience research was applied to the data set which produced a superior empirical sensor model. This method, an optimized Parzen algorithm, enables high-resolution models to be generated from a limited number of measurements.

In addition to developing these operational capabilities, the paper presents and discusses a means of implementation for immediate use. The proposed COULD-BE operational procedure is presented as a feasible way to insert the new capabilities directly into the operational and tactical Observe Orient Decide Act (OODA) loops.

Significance of Results: The results of this paper begin to lay the groundwork for the future use of new remote sensing capabilities. The methodologies developed to exploit the RS2 and AIS sensors were shown to be effective, but still require further development. However, even at the current state of development, using remote sensing capabilities in conjunction with airborne surveillance has the potential to increase the effectiveness of airborne patrol platforms.

Being able to correlate a “known” ship with an “unknown” report up to 8 hours apart is a difficult task. The new correlation procedure, using a dead-reckoning over great circle routes, has the potential to enhance the fusion operator’s task of identifying traffic in a Recognized Maritime Picture (RMP), where ships cover large distances.

In addition to the utility for remote sensing, the methodology has several potential spin-off applications. The optimized Parzen algorithm is favourable over to many commonly used methods: It produces more accurate models without a need to parameterize (a common source of systematic error); It produces an optimal result without the need for manual adjustment (i.e. it runs in an automated manner); and, it is designed to work even with a limited number of experimental measurements. The application of these Parzen derived models for simulation, characterization, and advanced fusion algorithms should be explored.

Future Work: Opportunities for future work were identified in several areas. Operational processes and procedures could be further refined, including the development of training to support them operationally. With further analysis, the incorporation of additional sensors could potentially be used to improve cuing. Better sensor models and further analysis of their employment could also be used to guide development of future sensor capabilities, such as the RADARSAT Constellation. The decision aids developed in this project should be further developed, particularly with the possibility of creating an efficient way to update and generate decision aids using new and relevant data as it becomes available. Track fusion algorithms are another area where additional study to enable better automation would be beneficial. In general, it was found that OR support to Operation Driftnet was very useful to the operator, and should be continued in future to progress the development of cued operational processes, and build upon the advances made here.

Sommaire

Near Real-Time Multi-Sensor Fusion for Cued Reconnaissance: Operational Analysis of Operation Driftnet 2009

S.A. Horn, A. Zegers ; DRDC CORA TM 2010-252 ; R & D pour la défense Canada – CARO ; novembre 2010.

Contexte : La pêche au filet dérivant est une technique de pêche très dommageable qui a des répercussions graves sur de nombreuses espèces marines. En 1991, l'Organisation des Nations Unies a adopté la résolution 46/215 qui imposait un moratoire sur la pêche au filet dérivant à grande échelle dans les eaux internationales. L'application de cette résolution est une tâche multinationale qui est assurée par le Canada, les États-Unis, le Japon, la Russie, la Corée du Sud et la Chine dans le Pacifique Nord. L'opération Driftnet est une initiative binationale Canada-États-Unis qui est réalisée par le ministère des Pêches et des Océans (MPO), le National Marine Fisheries Service (NMFS), la Garde côtière américaine (USCG) et les Forces canadiennes (FC).

Au cours de l'opération Driftnet 2009, l'aéronef de patrouille à long rayon d'action (APLRA) CP-140 Aurora a été utilisé pour patrouiller la vaste région du Pacifique Nord à la recherche de navires pratiquant la pêche illégale. Habituellement, les opérations du CP 140 sont menées depuis les îles Aléoutiennes, mais en raison de travaux d'entretien sur les pistes d'atterrissage, les opérations de 2009 ont été menées depuis Hawaii. Cela a éloigné davantage le CP-140 des zones historiques de pêche au filet dérivant, allongé le parcours de l'aéronef pour se rendre dans les zones de patrouille, et donc réduit proportionnellement la durée et la zone de la patrouille.

Pour atténuer les effets découlant de la réduction du temps de patrouille du CP-140, des systèmes de télédétection actifs et passifs ont été utilisés pour orienter plus efficacement le CP-140. Deux systèmes relativement nouveaux ont été mis à l'essai, soit le satellite RADARSAT-2, qui transporte à son bord un radar à synthèse d'ouverture (SAR), et le nanosatellite CanX-6/NTS de COM DEV qui est doté d'un système d'identification automatique (SIA) pour le suivi des navires et qui est capable de capter depuis l'espace les signaux SIA émis par les navires. La combinaison des données produites par ces deux capteurs très différents qui fournissent des renseignements de nature différente jusqu'à huit heures d'intervalle est très ardue, mais pas impossible.

Principaux résultats : L'équipe de recherche opérationnelle (RO) de la Force opérationnelle interarmées (Pacifique) (FOIP) a pu mettre en corrélation ces deux capteurs et analyser leurs caractéristiques et capacités. En tout, deux capacités clés ont été démontrées, soit la fusion de données en temps quasi réel et la production d'aides statiques à la prise de décisions opérationnelles. Au final, il a été démontré que ces deux capacités étaient utiles pour l'identification de cibles dignes d'intérêt pouvant être transmises au CP-140 à des fins d'interception.

Les principaux résultats des travaux sont les suivants :

1. Élaboration et mise en œuvre d'une méthode permettant la fusion des données produites par différents capteurs.

2. Utilisation des résultats de la fusion de données et des aides statiques à la prise de décisions pour identifier des cibles dignes d'intérêt et les communiquer à des aéronefs de reconnaissance.
3. Élaboration d'un processus opérationnel permettant d'utiliser des systèmes de télédétection pour orienter un aéronef de patrouille avant et pendant les patrouilles, et démonstration de sa faisabilité.

Les résultats découlant de l'utilisation des capteurs et de la fusion des données ont produit un ensemble considérable de mesures montrant l'ampleur des différences entre les capteurs. Ces mesures ont été utilisées en appui au processus décisionnel. Une technique novatrice dérivée de la recherche expérimentale en neurosciences a été appliquée à l'ensemble de données afin de produire un modèle de détection empirique amélioré. Cette méthode, qui constitue un algorithme de Parzen optimisé, autorise la création de modèles haute résolution à partir d'une quantité limitée de mesures.

Outre le développement de ces capacités opérationnelles, le document se penche sur une méthode potentielle de mise en œuvre de ces capacités pour une exploitation immédiate. Cette procédure opérationnelle ÉVENTUELLE pourrait permettre d'intégrer de nouvelles capacités directement dans la boucle "observation, orientation, décision et exécution" (ou boucle OODA).

Portée des résultats : Les résultats de ces travaux jettent les bases de l'utilisation future des nouvelles capacités de télédétection. Il a été démontré que les méthodes mises au point pour exploiter RADARSAT-2 et les capteurs AIS sont efficaces, mais celles-ci doivent néanmoins être peaufinées. Toutefois, l'utilisation d'outils de télédétection, de pair avec des techniques de surveillance aérienne, pourrait permettre d'accrotre l'efficacité des plateformes de patrouille aéroportées.

Il peut être très difficile de mettre en corrélation un navire "connu" avec un rapport de cible "inconnue", huit heures plus tard. Or, la nouvelle technique de corrélation, qui mise sur une valeur estimée au-dessus des routes orthodromiques, a tout le potentiel indiqué pour permettre à l'opérateur d'identifier plus facilement le trafic dans le tableau de la situation maritime (TSM), o les navires parcourent de grandes distances. Outre son utilité pour la télédétection, la méthode mise au point pourrait déboucher sur toute une gamme d'applications potentielles. L'algorithme de Parzen optimisé est préférable à nombre de méthodes couramment utilisées puisqu'il produit des modèles plus précis qui n'ont pas besoin d'être paramétrés (ce qui constitue une source courante d'erreurs systématiques), qu'il produit des résultats optimaux sans aucun ajustement manuel (c.-à-d., qu'il est automatisé) et qu'il est conçu pour fonctionner même avec un nombre limité de mesures expérimentales. L'application de ces modèles dérivés de l'algorithme de Parzen aux fins de simulation, de caractérisation et de développement d'algorithmes de fusion évolués devrait être étudiée.

Travaux subséquents : Des possibilités de travaux ont été cernées dans plusieurs domaines. Les procédures et processus opérationnels pourraient être raffinés, et plus spécifiquement, on pourrait mettre sur pied des programmes de formation pour les appuyer sur le plan opérationnel. D'autres capteurs pourraient aussi être intégrés à l'initiative afin d'orienter plus efficacement les aéronefs, mais cela exigerait davantage d'analyses. Nous pourrions également utiliser des capteurs améliorés et analyser de façon plus poussée leur exploitation afin d'orienter le développement des capacités des capteurs de prochaine génération, comme ceux de la Constellation RADARSAT. Les aides décisionnelles mises au point dans le cadre du présent projet devraient aussi être développées davantage, notamment pour permettre la création et la mise à jour d'aides décisionnelles exploitant des données pertinentes et nouvelles au fur et à mesure qu'elles deviennent disponibles. En outre, il serait utile d'approfondir les recherches dans le domaine des algorithmes de fusion de pistes afin d'accrotre l'automatisation des systèmes. Dans l'ensemble, l'appui fourni par l'équipe RO dans le cadre de l'opération Driftnet a été très utile pour l'opérateur. Cet appui devrait être maintenu afin de stimuler le développement de processus opérationnels dirigés et de tirer profit des avancées effectuées dans le cadre des présents travaux.

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1 Introduction

In September 2009, Joint Task Force (Pacific) (JTFP) Operational Research (OR) Team was asked to support JTFP J3 Air operations during Operation Driftnet 2009. Specifically, analysis was requested to support the effective use of RADARSAT-2 (RS2) and Automatic Identification System (AIS) data for aircraft cuing, mission planning, and improving the Recognized Maritime Picture (RMP). This technical memorandum summarizes the analysis of these new capabilities, and their utility to operations. It also begins to lay the groundwork for the future use of new remote sensing capabilities.

1.1 Operation Driftnet

Driftnet fishing is a highly controversial fishing technique which has severe impacts to many species of sea life. In 1991, the United Nations (UN) passed a resolution banning driftnet fishing in international waters [1]. Enforcement of the resolution is a multinational task supported in the North Pacific by Canada, the United States, Japan, Russia, South Korea, and China. Operation Driftnet is a US-Canada bi-national operation conducted by Department of Fisheries and Oceans (DFO), National Marine Fisheries Service (NMFS), Canadian Coast Guard (CCG), United States Coast Guard (USCG), and the Canadian Forces (CF). As part of the operation, the CP-140 Long Range Patrol Aircraft (LRPA) is used to conduct surveillance in suspected areas of driftnet activities.

One of the major constraints for the operation is the range of the CP-140 aircraft. Operation Driftnet 09 was conducted in the Pacific Ocean with CP-140 flights based out of Hawaii due to runway repairs at its preferred site in the Aleutian Islands, which is closer to traditional fishing areas. Because the operation had to based further away from the fishing areas, a long transit was required to reach fishing areas. The increased transit time reduced the overall time available to patrol, and reduced the size of the patrol areas. To mitigate the effects from the reduced CP-140 patrol time, and because the CP-140 platform is expensive to operate [2], it was decided that the aerial surveillance platform could be used more effectively by cuing flights based on pre-acquired intelligence of the area of operation. For Operation Driftnet, it is important the this cuing intelligence be releasable and unclassified, so that it can be shared with the Other Government Department (OGD) participants, and used for possible legal proceedings. For this reason, RS2 and AIS data are suitable intelligence sources, since they are collected using unclassified technology.

The goal of the operation was to cue the aircraft to fly on targets that were likely to be fishing vessels. Fishing vessels tend to be relatively short compared to merchant traffic in the operating area. Based on operator experience, it was decided to use a ship length of under 250 feet as a cuing indicator to direct patrols to possible fishing fleets. This cutoff length was also validated with a query of about 6000 ships in Lloyds database, which revealed that 95% of fishing vessels are less than 250 feet long. Other cuing indicators of fishing vessels, such as clusters of ships, and lack of AIS, were also used.

Any increase in platform effectiveness could not be measured directly, since there was no previous Hawaii-based Operation Driftnet to compare against. However, since the aircraft was focused in its surveillance role, it is expected that the number of Target of Interests (TOIs) intercepted per hour of flight was higher with than without cuing.

1.2 Data Sources & Assets

Three surveillance platforms were used for Operation Driftnet 09, two separate remote sensing satellites, and the CP-140 airborne platform. The two remote sensing capabilities were RS2, and space-based AIS from COM DEV. Both of these sources are relatively new and their utility to support operations has yet to be quantified. The geographic distribution of the data sources is shown in Figure 1, and the chain of communication is shown in Figure 2.

- **RADARSAT 2**: The Canadian RS2 Satellite provides Near Real Time (NRT) ship detection using Synthetic Aperture Radar (SAR). It provides information on ship positions, their probable courses, and the length of the ship. It does not provide the name (identity) of detected ships. The Polar Epsilon project [3] coordinated the acquisition of RS2 imagery and delivery of the NRT product to the Operation Driftnet operators by email in Over The Horizon (OTH) Targeting GOLD (OTH-T-GOLD) (OTG) format [4]. The RS2 satellite was operating using the ScanSAR Narrow mode and the data was processed by Polar Epsilon using OceanSuite [5].

  The RS2 satellite has a sun-synchronous circular polar orbit, with a period of approximately 100 minutes. Because the orbit is sun-synchronous, and the satellite orbits over day/night and night/day transitions, the imagery will always be near dusk or dawn. The satellite repeats its cycle every 24 days, and the time between visits depends on latitude, with polar regions being visited more frequently. The area of ocean targeted by Operation Driftnet 09 had 2-3 observations per day. The RS2 swath areas covered by each observation varied depending on the mode of operation. The imagery obtained during Operation Driftnet 09 covered areas of roughly 300km wide by 900km long [1].

  The ground station (for imagery download and programming) was located in Gatineau, Quebec. Acquisition planning can be conducted in as little as 24 hours, with a 3 hour “emergency ordering” capability. For Operation Driftnet 09, the satellite imagery was planned and ordered roughly a month ahead of the operation.

  The latency from RS2 observation to delivery of the position reports to operators was typically around eight hours, but occasionally could take longer, up to 24 hours. This latency depended on many factors, such as the availability and shift schedule of imagery analysts at Polar Epsilon.

- **Commercial AIS**: This is the first operational trial by JTFP using commercial space-based AIS. AIS is a self-reporting system in which transponders on ships transmit identity and position information [7]. The AIS data was provided by COM DEV as an operational demonstration of exactEarth, a subsidiary of COM DEV, which used the CanX-6 Nanosatellite Tracking of Ships (NTS) [8] AIS satellite to collect AIS signals in space [9]. It covers a 5000 km wide diameter field of view, and captures 90 second snapshots of AIS data. The CanX-6 project is run out of the University of Toronto Institute for Aerospace Studies Space Flight Lab, and is a collaboration between academia and COM DEV.

  The CanX-6 NTS satellite is in a circular polar orbit similar to that of RS2, but the orbit is not sun-synchronous, therefore it does not align with RS2. Depending on the location in

[1]For purpose of this operation, RS2 was configured for use in wide-area surveillance (ScanSAR Narrow with pixel resolution of 25m by 25m) [6]

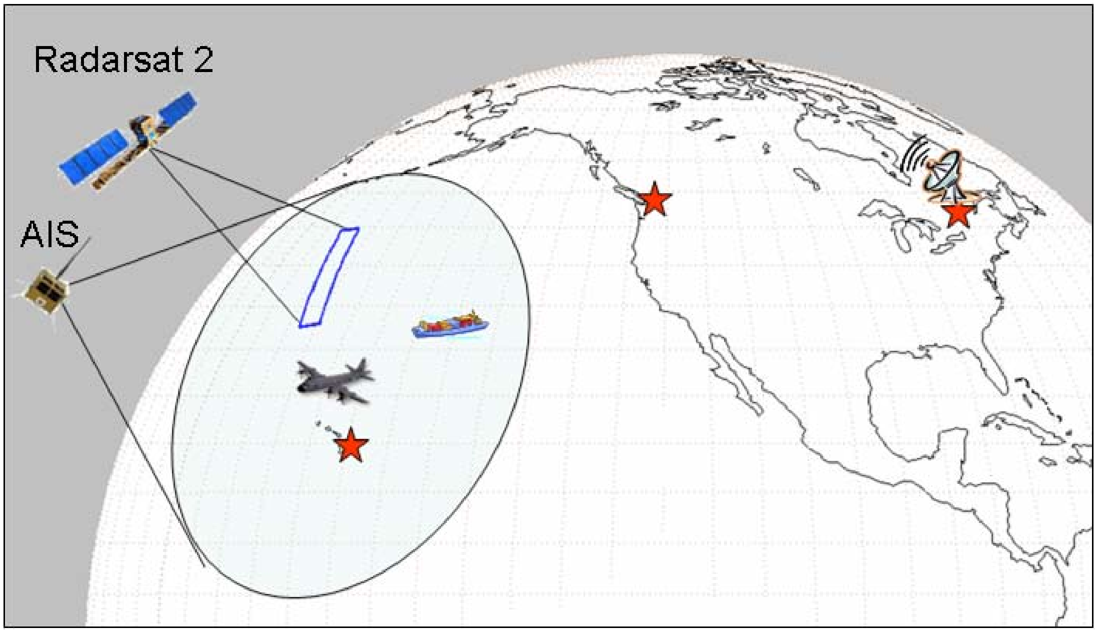

Figure 1: *Overview illustrating the geographical distribution of resources during Operation Driftnet 09.*

the world, there could be up to 12 hours difference between passes of the RS2 and CanX-6 satellites.

Only type 1, 2, and 3 AIS messages are processed by COM DEV. These AIS messages provide the Maritime Mobile Service Identity (MMSI) number, the reported position, speed over ground, course over ground, true heading, and rate of turn, as well as some additional fields. Key fields such as ship name, International Maritime Organization (IMO), and length are not provided in message types 1, 2, or 3. To provide these fields, the MMSI number was fused by COM DEV to the names of ships in their commercial database before delivery to Operation Driftnet in OTG format. Operational Research analysts did not have access to this database, and thus could not validate its accuracy.

- **CP-140 LRPA**: The CP-140 is the Canadian variant of the Lockheed P-3 Orion. It is well equipped for conducting long range maritime patrols with a 14 hour flight time and a range of over 9,000 kilometers. The aircraft can detect ships using radar, optical sensors, or visual observation. The aircraft was not equipped with an AIS receiver during Operation Driftnet 09, but AIS capability is currently being added in a refit program. The CP-140 was based out of Hawaii during Operation Driftnet 09.

1.3 Operational Process at Start of Operation Driftnet 09

The operational process at the start of Operation Driftnet 09 can be described in terms of an Observe Orient Decide Act (OODA) loop, as illustrated in the left side of Figure 3.

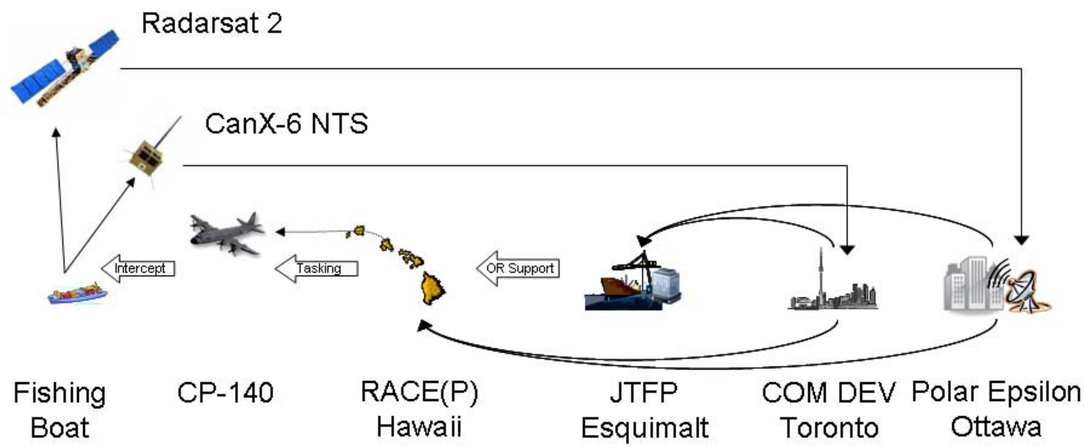

Figure 2: *Diagram illustrating information flow during Operation Driftnet 09.*

1. **Observe**: This stage consists of the collection of remote sensing data from RS2 and AIS. The RS2 and AIS data is sent from Polar Epsilon and COM DEV to Operation Driftnet in Hawaii. At this stage, there is not yet an aircraft on patrol. In addition to the RS2 data that is received well before the flight, an additional RS2 pass will typically occur after the aircraft takes off to provide updated information.

2. **Orient**: The data is used by the operators to generate situational awareness and gain a sense of the traffic distribution. The data is visualized using Google Earth, and only the positions of the ships during the last satellite pass are known. There is no dead-reckoning capability, and fusion is limited to what can be done visually in Google Earth. Since the fusion capability is limited, the operators are unable to determine which of the RS2 reports do not associate with AIS, and instead are relying on the length estimates provided by RS2 to determine if they are potentially fishing boats. RS2 can also show "clumping" of traffic which is another possible indication of a fishing fleet.

3. **Decide**: Using the satellite snapshots, which are up to 8 hours old, and the limited fusion between the sensors, the operators draft up a flight plan for the CP-140. The plan consists of directing the aircraft to areas that have more traffic, or are more likely to contain fishing boats.

4. **Act**: The final step of the loop is to fly the CP-140 based on previous information in the hopes that any driftnet fishing in the area will be observed. If driftnet fishing is detected, evidence is collected for prosecution.

This operational process has several weak points. First, the lack of effective fusion between AIS and RS2 limits the exploitation of the data. Second, the use of RS2 reported ship lengths was known to be error prone and there was little information on the accuracy of that information. Third, the morning RS2 pass happens after the plan has been established and the aircraft takes off. If the operators had the fusion tools, then this up to date information could be quickly analyzed and

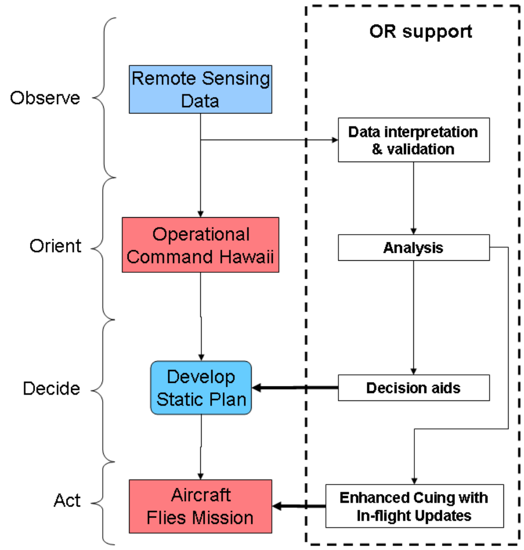

Figure 3: *AS-IS operational process diagram.*

passed to the aircraft already on patrol to provide last-minute cuing in the event a high priority target is identified.

1.4 Operational Support Request to Operational Research

To effectively use the CP-140 aircraft in the interception of driftnet fishing, operational research was asked to provide support and advice on the use of sensors to cue the aircraft. To address the weak points in the AS-IS process, the following OR support activities (shown in the right side of Figure 3) were undertaken:

1. **Data interpretation & validation**: The AIS and RS2 data was made available to the OR Team in Esquimalt. The data was then processed in order to be imported into OR analysis tools.

2. **Analysis**: Using OR tools in development, the data was fused and analyzed to produce two products: Decision aids for using RS2 lengths to identify potential fishing boats, and visualization of the data after fusion to identify RS2 contacts without AIS, which are potential TOIs to pass to the aircraft. These TOIs could potentially be fishing vessels, since fishing vessels are not required to have AIS, or they could be merchant vessels that are not complying with AIS requirements. Section 2 describes in detail how this was done.

3. **Decision Aids**: The intelligence used to cue the patrols was based on remote observation of ship lengths, since fishing vessels are generally smaller than merchant shipping. The desired result for the operators was to use a sensor to eliminate white shipping traffic, and conversely, identify all ships that were 250 feet long or less. However, the algorithms that *approximate* the ship length from RS2 imagery are based on RADARSAT-1 (RS1) experimentation [5], and the are still in the process of being optimized and refined. In general, length estimations using

SAR data for such a wide area will always be somewhat inaccurate. Since the RS2 reported length is an inaccurate measurement, it will require a good understanding of uncertainty in order to be used in future operations. Decision aids were developed based on the risk of misclassifying a fishing boat using RS2 ship lengths. Sections 3.2 and 4.3 describe these decision aids in more detail.

4. **Enhanced Cuing with In-flight updates**: Using the advanced OR analysis tools under development, anomalies in the data were identified that would have been otherwise difficult to detect. These anomalies were then passed to the operational command in Hawaii for further investigation. Section 5 discusses how the operational process can be improved to make use of this NRT information for cuing patrols.

The analysis and support provided in Operation Driftnet 09 targeted the development of the static plans using decision aids, and the identification of potential targets and forwarding analysis to the operational command for aircraft cuing. In addition to enhancing and supporting operations using the current process, the analysis and new data sources allowed for new ways to improve the process.

During Operation Driftnet 09, the operators decided to attempt a conversion of a time late unknown RS2 contact into a TOI and then intercept the target. Unfortunately, when this procedure was trialled, there was no unknown RS2 contact available. To test the new operational process, the RS2 reported position of a randomly chosen known contact was passed in-flight to the aircraft, with instructions to intercept and identify. The aircraft located and intercepted the chosen vessel after a 2-hour search. The target was visually identified, which confirmed that the implementation of the process is feasible. Annex B shows the mission report from this trial. The enhancements to the operational process are discussed in Chapter 5.

2 Data and Sensor Fusion

The goal of fusion was to enable the identification of RS2 contacts which were emitting AIS information, and those that were not; thereby increasing the priority for a flyover by the CP-140. Fusion was also required for the analysis of the RS2 reported lengths. The RS2 contacts were correlated with AIS contacts so that the AIS information could be checked against tombstone length information and thereby validate the accuracy of the RS2 reports.

The work described in this section is broken down into 3 tasks:

1. **Data collection and processing**: This involves mainly the collection of the RS2 and AIS data, which is described in 2.1. The data has to overlap both temporally and spatially in the area of interest to be relevant for correlation. The degree of overlap plays a key role on the quantity and quality of data that can be used for analysis.

2. **Data fusion**: This involves fusing the AIS information with known databases to extract tombstone information about the ships. AIS reporting has several unique challenges [10, 11] and the quality and "trust" of this information will play a key role as well in the quality of data for analysis. Additionally, the quality of, or lack of tombstone data may also reduce the quantity of useful data. This task is described in 2.2.

3. **Sensor fusion**: This involves the correlation of the RS2 reports and AIS reports based on time, position, and any other identifying attributes. This step is essentially a track fusion problem with limited data points in disparate time and space. The quality of the method or algorithm to conduct the track association may impact the quantity and quality of data for analysis. This task is described in 2.3.

2.1 Data Collection and Processing

Data from RS2 and COM DEV AIS were received in OTG XTC [4] format by email from Polar Epsilon [3]. The COM DEV AIS data was also provided in a Google Earth .kml file so it could be viewed by the operators in Hawaii.

For analysis, the data had to be imported into a format usable by the OR analysis tools. The data was imported into a MySQL [12] database using MATLAB® [13] and the Prototype RMP Analysis Toolset (Prototype RAT), an analysis tool developed in-house by Joint Task Force (Atlantic) (JTFA) and JTFP Operational Research Teams (ORTs) [2].

The Structured Query Language (SQL) database schema used in Prototype RAT is a cloned version of the operational database used to archive the Canadian RMP in the Global Command and Control System (GCCS). Once the data is converted from OTG format and inserted into the database, the information can easily be queried using SQL, or accessed directly from MATLAB®using Prototype RAT.

[2] Prototype RAT and other similar analysis tools are under development by Defence Research and Development Canada (DRDC) Centre for Operational Research and Analysis (CORA) and currently being documented [14]. Some information about Attribute Correction Engine (ACE) can be found in a paper describing the exploitation of AIS with Electronic Intelligence (ELINT) [15].

2.2 Data Fusion

The accuracy of the length field provided by RS2 was uncertain at the start of Operation Driftnet 09. To determine the accuracy of the lengths, they needed to be compared with the known lengths of the ships. The length of the ships was found by first identifying the ships using AIS, and then obtaining the length from Lloyd's shipping database.

The following procedure was performed to fuse the length information to the AIS reports: A three-step procedure was performed to fuse the length information to the AIS reports:

1. **AIS Data Collation:** The first step was simply to collate a list of unique ships detected by AIS. This list included the reported vessel names, IMO, and MMSI.

2. **Data Mining:** To get more information on the list of ships, is was necessary to gather information from other data sources. For the purposes of this analysis, it was decided to use Lloyd's database, since it is readily accessible and extensive. A limitation of the Lloyd's query interface is that it is only possible to query on one field at a time. This makes it difficult to directly query for unique vessels since there are many entries with duplicate information (for example there may be multiple entries for different ships with the same name). To provide relevant results, the query algorithm (found in Annex C) queried first by IMO, and if there is no result, the algorithm moves on to try the MMSI, and then finally the ship name as a final resort, as illustrated in Figure 4. This step results in a longer list of ships than the original AIS contacts, which are then fused with the AIS contacts in the next step.

3. **Data Fusion:** The data from Lloyd's database was then imported into Additional Reference Table (ART), a component of Prototype RAT. Another component of Prototype RAT called ACE compared the AIS report table against ART to fill in any missing fields in the AIS reports (including ship length). The ACE algorithm uses all the AIS fields, in combination, accounting for mis-spellings, transcription errors, and incomplete fields, to uniquely identify which ART entries correspond to the AIS ships. Any discrepancies or errors detected in the AIS data are automatically corrected. Additionally, missing fields in the AIS data (such as call sign, ship length, flag, IMO, etc.) are filled in. This is effectively the same as using Lloyd's database as the authoritative tombstone data. The ACE algorithm is shown in Figures 5 A&B.

Figure 5A is a high-level diagram of ACE and Figure 5B shows ACE ART in higher detail. This is the component of ACE that attaches the length information in ART to the AIS reports. Once the data is cleaned up and complete, it is ready to be analyzed further using Prototype RAT.

This method relies AIS augmented with Lloyd's data to supply tombstone information for the analysis. The fusion method used will reduce occurrence of errors in the data, however the possibility of errors cannot be completely eliminated. Although this risk of inaccuracy has been assessed to be quite low, it needs to be recognized as a potential source of error.

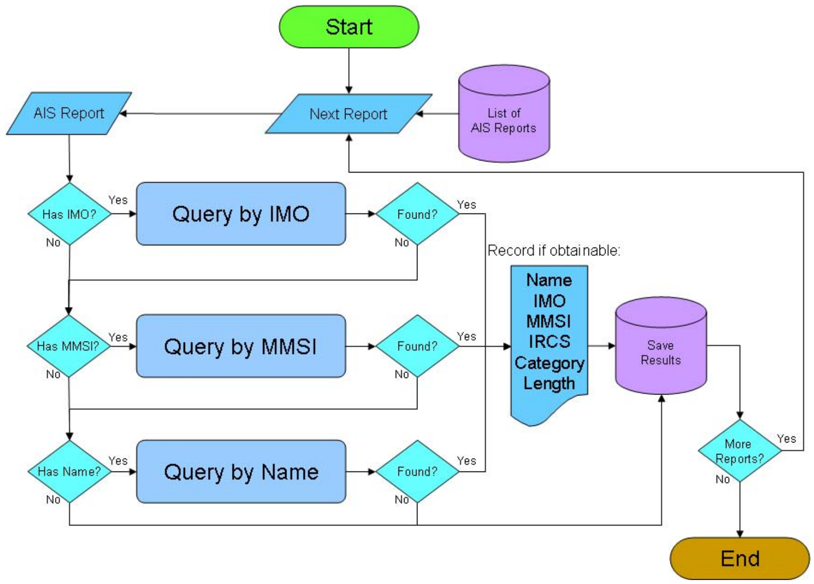

Figure 4: *Flowchart illustrating the general-purpose algorithm used to query Lloyd's database. This algorithm can also be applied to non-AIS reports.*

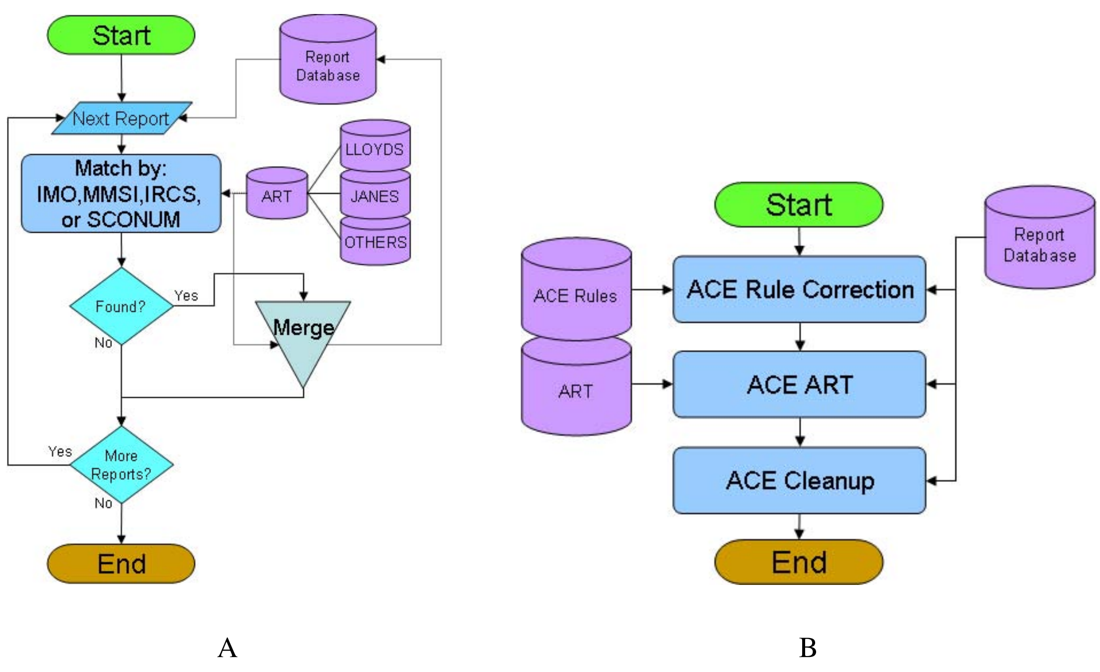

Figure 5: *Flowcharts illustrating the ACE algorithm (A), and the details of the Merge process (B).*

2.3 Sensor Fusion

To correlate the RS2 and AIS information, sensor fusion must be preformed to determine which of the reports correspond to the same ship.

The data from both RS2 and COM DEV AIS was used in combination to generate a list of possible ships in a patrol area. The RS2 and CanX-6 satellites both orbit on circular polar orbits, and the RS2 satellite is sun-synchronous. The RS2 satellite provided one pass of the operating area in the morning and one to two passes in the evening (with each pass moving progressively westward). During Operation Driftnet 09, the first morning pass was usually near the longitude of Hawaii, and the second evening pass near Japan. The CanX-6 micro satellite provided one pass per day and covered all the area between Hawaii, Japan, and the Aleutian Islands. Because of the nature of the orbits of the two satellites, there were significant gaps in the arrival of data between each source. These gaps were as short as a few hours to over 12 hours long, as shown in Figure 6. It is easy to see that the evening overlaps were the closest together, providing the best opportunity to correlate data from the two satellites.

To cue the aircraft, it is useful to identify which RS2 reports correlate to AIS reports and which reports are for unidentified vessels and possibly of interest. Unfortunately, the pairing of interest for cuing the CP-140 was the RS2 morning pass, which was about 8 hours after the AIS data.

Because of the large gaps between sensor coverage, and the lack of identification from RS2, this meant that sensor fusion was not straightforward. While algorithms like Multi Sensor Integration in a Common Operating Environment (MUSIC) [16–18] have been developed, there is still no Command and Control (C2) system configured to provide the automated data fusion required by the Operation Driftnet 09 operators. Since the fusion task requires significant operator actions, the fusion task was simply too complicated to automate in GCCS. Therefore, to correlate the RS2 reports (with no identification) to the AIS reports, “manual” (human in the loop) sensor fusion was required.

JTFP ORT worked around the fusion limitations in the current C2 system by using a simple manual Standard Operating Procedure (SOP) to perform the sensor fusion as follows:

1. The AIS reports and RS2 reports are plotted in Prototype RAT.
2. A dead-reckoning algorithm using great circle routes is used to predict where the AIS contacts would be at the time of the RS2 pass either before or after the AIS pass [3]. The reckoning is displayed as a dotted line and a red X on the expected position. Note that RS2 reports could not be accurately projected because the sensor does not provide any speed information. However, the reckoning algorithm works both forwards and backwards in time, so AIS reports could also be reckoned to RS2 reports in the past, thereby providing an ID on past reports.

[3] The dead-reckoning uses a great circle route to predict position as this compensates for course corrections of ships as they transit. In order to save fuel and time, ships travelling over large distances tend to follow great-circle routes, as they are the shortest distance between two points on the globe. Since the ships in the JTFP Area of Responsibility (AOR) are travelling over large distances, and the AIS and RS2 contacts may be separated by significant distances, it makes sense to use great-circle routes for the dead-reckoning. Additionally, with the advent of Global Positioning System (GPS), navigation using great circle routes is trivial and commonplace. This method is in accordance with practical and published practice [19].

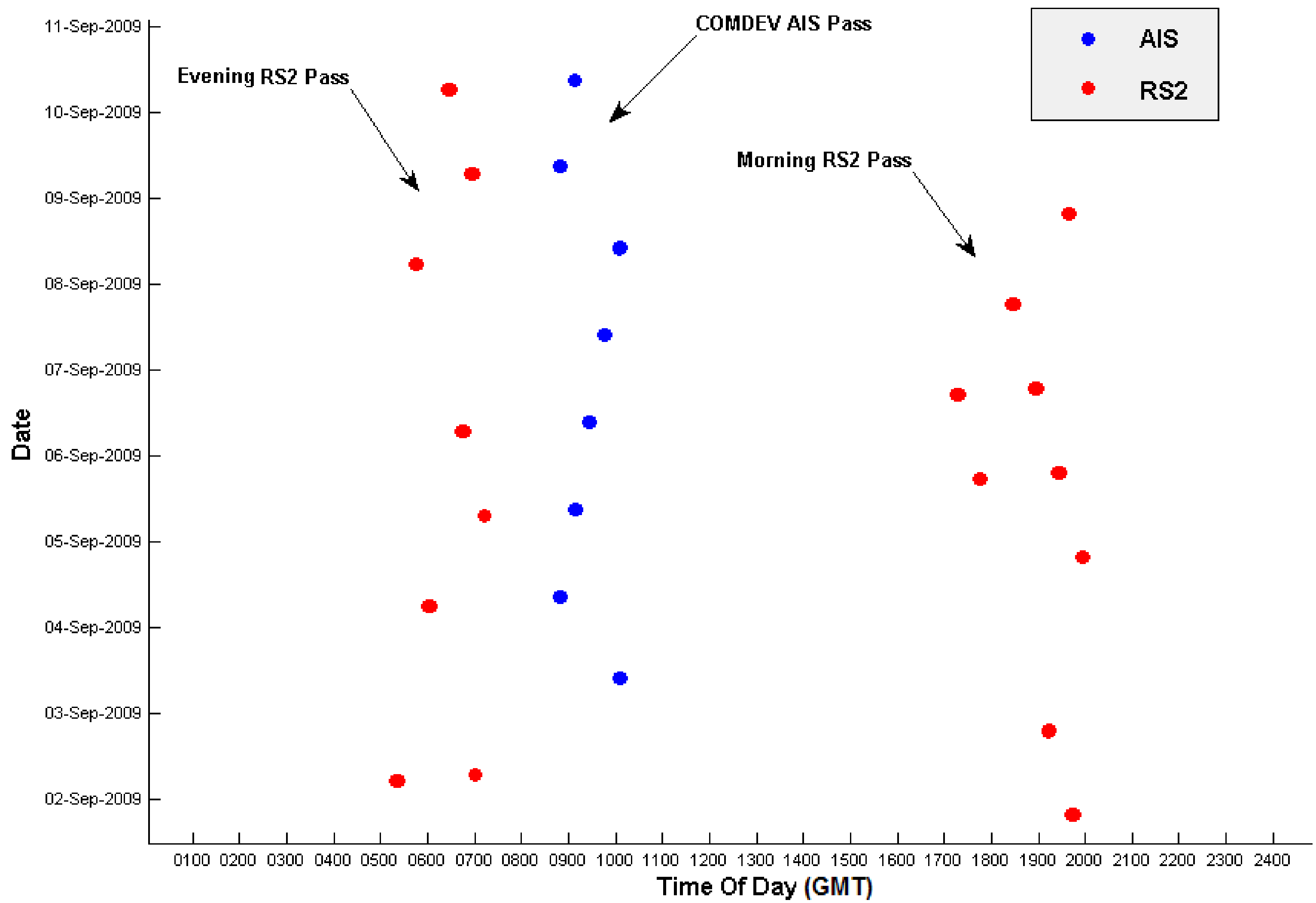

Figure 6: *A scatter plot illustrating the time of day (GMT) that satellite passes were collected.*

3. If a red X aligns with the RS2 report, the AIS and RS2 reports were accepted as a correlation. In the rare case of two X's on a report, no correlation is made and the data point is ignored.

4. If a red X falls within the predicted RS2 swath and does not have an associated report, it is considered as an AIS report without RS2. Since swath edges were estimated in Prototype RAT, there is not enough confidence that red X's near the edge of the swath are missed ships, and they are therefore omitted from the analysis.

5. RS2 reports that do not correlate to an AIS contact are also recorded. This information is useful when generating a TOI, especially when RS2 reports a very long ship without AIS active.

6. If a red X falls on the RS2 report, then the two are correlated and the RS2 length can be compared to the tombstone length. These correlations are analyzed in near real time as described in Section 3, and post operation as described in Section 4.

Figure 7 shows an image illustrating the results from steps 1 to 5 in the algorithm. There are 4 correlations shown. The area between the blue lines illustrates the estimated area covered by the RS2 swath. For each of the RS2 passes with available AIS information, the course, speed, length, and identity of correlated ships were recorded in a Microsoft®Excel spreadsheet. Once all of the correlations were tabulated, further analysis was done using both Excel and MATLAB, as described in the following section.

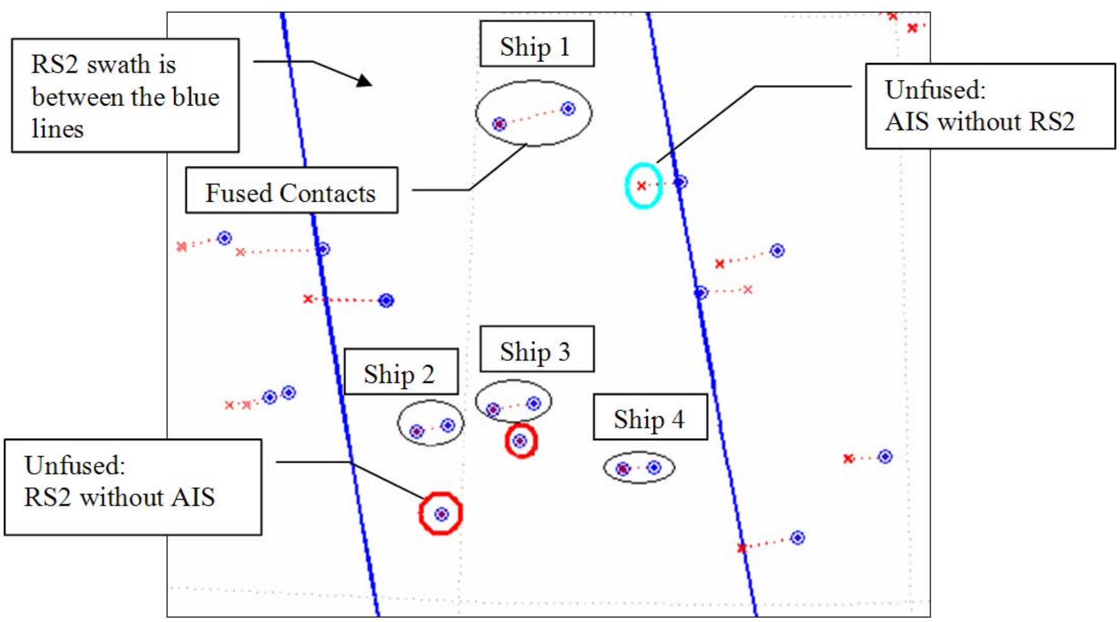

Figure 7: *Example of AIS to RS2 correlations.*

3 Operation Driftnet 09 Operational Support

The operational goal of Operation Driftnet is to monitor the ocean for illegal fishing activity. Therefore, it is likely that ships participating in this illegal activity are relatively small fishing boats. Due to CP-140 constraints, the operators wanted to generate the best Situational Awareness (SA) possible before flying. This led to the use of AIS and RS2 satellite passes before flying to cue the CP-140 patrols. The most up to date source of information before flying was a RS2 satellite pass the morning of the patrol.

The most straightforward use of information provided by RS2 was to look for "clumps" of ships, which could indicate a fishing fleet. Additionally, given the length of ships reported by RS2, and given some knowledge about the accuracy of ship reports, one can determine which known ships in the area are more likely to be fishing vessels possibly engaged in illegal activity. It was decided, for practical purposes, to use 250' or less as the criterion for Operation Driftnet patrols. The goal was to use RS2 to detect the position of all ships with calculated lengths that are around 250 feet or less, and alternatively, identify where the merchant traffic is located. These ships may or may not have AIS. This information can be used to plan a surveillance flight to maximize the interceptions on potential fishing vessels, and even identify specific TOIs for intercept.

The previous section described the OR methodology used to process the AIS and RS2 data. This section uses the fusion results from AIS and RS2 to characterize the RS2 ship length accuracy.

3.1 Characterizing the Information Provided by the Sensors

This report is not the first to characterize the observed ship lengths from SAR imagery using comparisons with AIS. DRDC Ottawa [20, 21] has previously performed some analysis of the Envisat Advanced SAR (ASAR) system and RS1. They are also working on a correlation analysis between RS2 and AIS data [22]. Their efforts are focused on improving the sensor characteristics while the analysis in this paper focuses on the exploitation of the sensor directly for operational purposes.

Comparing the length of ships observed with RS2 and AIS is difficult because RS2 does not identify ships, therefore, the actual length of the ship is not immediately known. Without identification, the operator has to be able to use a measurement which is known to be inaccurate (RS2 length) to infer what the actual values for ship length could be.

Section 2 described the method in which the AIS and RS2 data can be used to make comparisons between the tombstone length and the RS2 reported length. To characterize the RS2 length accuracy, the *relative deviation* of reported lengths was selected as a useful measure, which is calculated as:

$$d = \frac{Actual - Measured}{Measured} \tag{1}$$

The relative deviation will range from -100 % (actual length far less than RS2 reported length) to several hundred percent (RS2 reports no length). Negative values indicate that RS2 is over-estimating the ship's length, while positive values mean that RS2 is under-estimating length. This

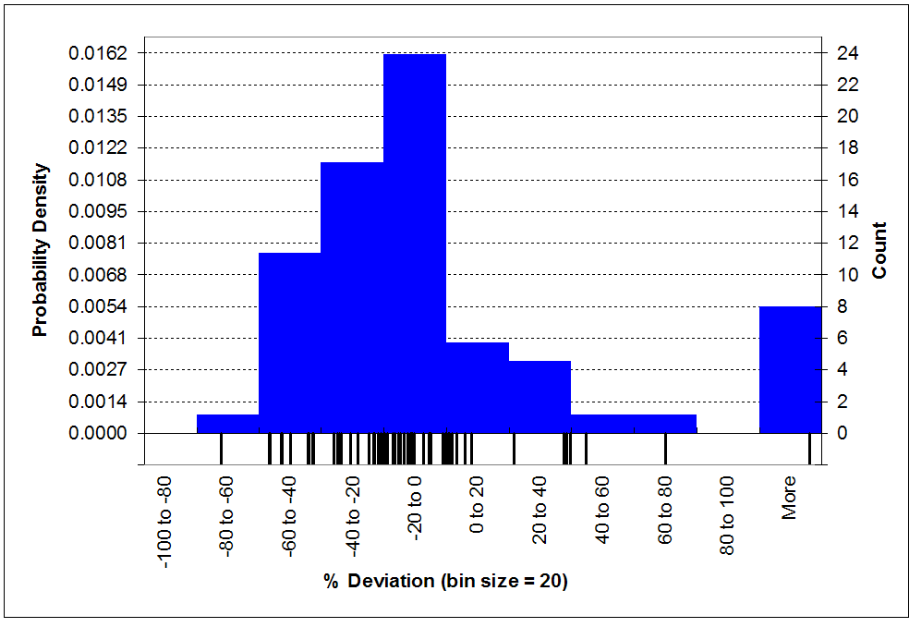

Figure 8: *Histogram method approximation of the PDF from measurements of RS2 length deviations. Negative deviations indicate cases where RS2 is over-estimating the ship's length, while positive values mean that RS2 is under-estimating length. The lines below the histogram are a one dimensional representation of the raw data points used to generate the histogram.*

equation treats the measured length as the baseline value, and calculates the deviation of the actual length from the measured length. RS2 length estimation work by Vachon and Wolfe [20] use *measurement error* vice *relative deviation* as an accuracy metric. They are measuring the error level of the sensor relative to a known value, while this work focuses on estimating the known value given a sensor measurement. This is perhaps unusual, but was done deliberately in order to generate metrics and decision aids that would be easy for operators to interpret. Since the measured length is the only value the operators see, it is more natural to treat that as the baseline, and to consider the variation of possible actual lengths from that baseline. In other words, given a measurement by RS2, one can easily determine the likely range for the actual ship length.

The more measurements of deviations that are made, the better the understanding of the RS2 system (sensor and OceanSuite algorithm) will be. Using the fusion methodology described previously, several deviations were measured during the first week of the operation. As data was being collected from the satellite passes, a histogram of deviations was created and updated as additional measurements were made. After 65 measurements, the histogram shown in Figure 8 was generated. This histogram is a non-parametric approximation of the shape of the Probability Density Function (PDF).

There are many different non-parametric methods to approximate the PDF from a set of measurements, such as kernel estimators [23], or recursive Bayesian estimation [23, 24]. Using a non-parametric method to estimate the PDF frees us from the need to make assumptions on the nature of the PDF. For this analysis, the simple histogram estimation method was used, in which the area under the histogram is normalized to 1. The approximate PDF with a bin size of 20 (the optimal bin size [25]) is shown in Figure 8 by reading the left scale. The PDF gives the probability of a specific deviation for any given report (e.g. for -20% to 0% deviation, $0.0162 \times 20 = 0.324$, or a 32% chance that the relative deviation will be between -20 and 0).

3.2 Operational Decision Support

For a given RS2 report, if one hypothesises that a detected ship is our "target" with length l, and RS2 reported a length of L_{RS2}, then the deviation (following Equation 1) would be:

$$d = \frac{l - L_{RS2}}{L_{RS2}} \tag{2}$$

The probability that the actual length (L) is less than l, or $P(L < l)$ is found by integrating the PDF:

$$P(L < l) = \int_{-100}^{d} P(x)dx \tag{3}$$

where $P(x)$ is the probability density function.

Integrating the granular form PDF shown Figure 8, however, does not provide much useful information unless the resolution of the function can be increased. While the histogram method is useful for visualizing the shape of the probability density function, it has the side effect of averaging out some of the useful information in the data. To calculate the integral of $P(x)$, the actual measurements in Figure 8 were used vice the histogram approximation of the PDF. This is in effect the same as reducing the bin size to a very small value such that the height of each bin is $\frac{1}{N}$, where N is the number of measurements. Although a smaller bin size is preferable for integrating the PDF, there are only a few measurements, so there are "gaps" visible in the PDF. Even so, the integral shows virtually all of the information present in the data, thereby mitigating the limitations of the histogram estimation method.

The probability calculated in Equation 3 is equivalent to the *risk* that a ship detected by RS2 reported with a length L_{RS2} is not correctly classified as a short (fishing) vessel of length l. Given a certain risk of mis-classification, it was determined that a "cut-off" length for RS2 targeting could be used to filter the OTG messages based on reported length. For example, if one is targeting ships of 250 feet long or lower, the question is: "what is the risk that a RS2 reported length of 300 feet is not considered a TOI, but is actually less than 250 feet long".

From the data collected in the first week of the operation, the value of $P(L < l)$ for RS2 reported lengths between 0 to 1000 feet was calculated, and the results were provided to the operators in Hawaii. The results are plotted in Figure 9.

From this chart, it can be seen that the risk falls off rapidly as the RS2 reported length increases. During Operation Driftnet 09, the operations staff directed 400 feet be used as the "cut-off" length,

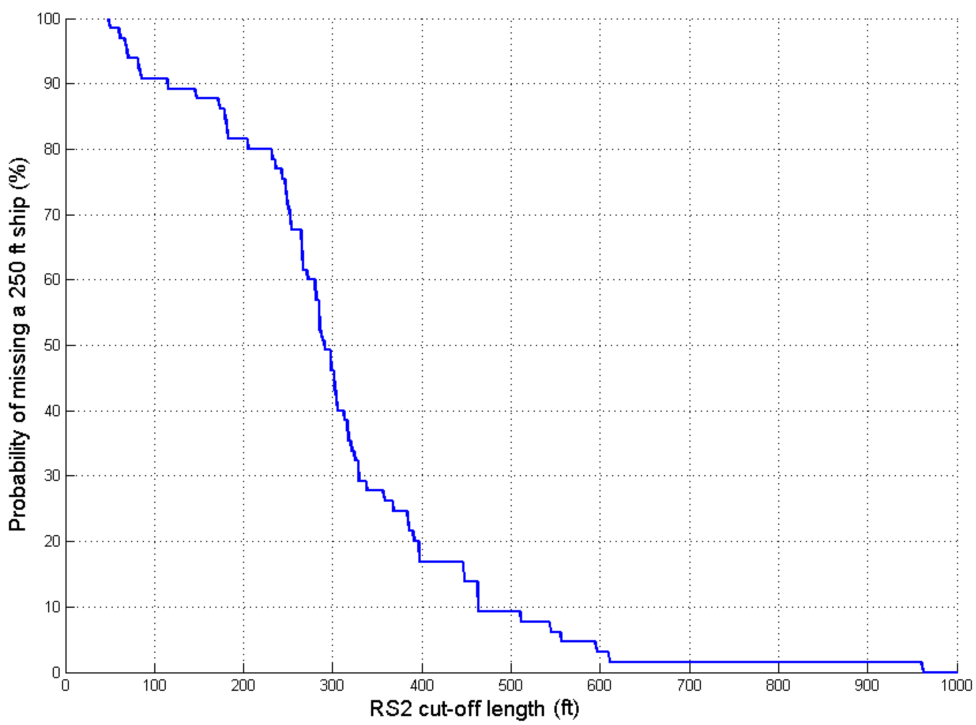

Figure 9: *Probability that a given RS2 reported ship is less than 250 feet given reported length.*

which translates to roughly a 20% risk that a given filtered contact could actually be under 250 feet in length. Alternatively, this targeting method identifies 80% of all the ships less than 250' long detected by RS2. Depending on the number of TOIs that can be added to the CP-140 flight plan, the level of accepted risk in flight planning can be managed.

It should be noted that there are a few limitations to the method used here:

- This was based on a limited analysis of 65 data points due to the need for quick results to guide the remainder of the operation. Further statistical analysis of the data points would improve the quality of the results.

- When the fusion process was performed, the most obvious fusion pairs in uncluttered open ocean were used. To perform detailed analysis in more cluttered area would take more analysis time and therefore, the easier fusions were performed first, with the hopes of later revisiting the same area when more time is available. Repeating the manual fusion process more thoroughly would provide more data points.

- The data was all collected during a one-week period. This data collected will thus depend on the operating conditions during this period, such as sea state, weather, ship type distribution, etc. It is possible that the statistical distributions found during this period may not hold during other time periods with different operating conditions.

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4 Post Operation Analysis

The previous section described the near real time support provided during operation Operation Driftnet 09. Due to the quick responses required for Operation Driftnet 09 support, only a cursory analysis could be performed. Only a select number of swaths were analyzed in accordance with data and time available. Following the conclusion of the operation, the analysis was repeated on the complete dataset of 31 RS2 swaths using the methods described in Section 2. Since the data was collected over several weeks and the weather was not consistent over this time, the complete dataset contained a convolution of sensor performance in various different conditions. Also, three of the 31 swaths were omitted because they were from a cluttered area with a significant amount of time between the AIS collections and the RS2 swath. It was assessed that trying to make correlations in these cases was both impractical and prone to excessive error.

The product of this analysis was a list of ships for which RS2 and AIS were correlated, as well as a list of ships which had only one or the other. This section discusses the results from the more thorough analysis of the RS2 and AIS data.

4.1 Analysis of Ship Lengths

In the same method used in the previous section, the deviation of lengths from the correlations was calculated. During the more detailed analysis, there were 199 correlations between the RS2 and the AIS data. For the correlations, there were 17 AIS contacts where the length of the ship was either unknown or not in Lloyd's database. Also, for unknown reasons[4], two of the RS2 reports had multiple length measurements. This resulted in 185 measurements of length deviations between the Ocean Works algorithm for RS2, and tombstone data.

Within the 185 measurements, there were 10 measurements for which the error was extremely high (which is approximately 5% of the data). There are many possible explanations for why some deviations were so large. One observed extreme error was for a 73 foot tug boat detected as a 710 foot RS2 contact. It was likely that the tug boat was probably pulling a longer ship or barge and so it not surprising that the AIS length did not match the larger RS2 length. It was debated whether or not to discard these measurements, but in the end it was decided not to discard them, as they represent realistic observations made using RS2.

The plot in Figure 10 characterizes and visualizes the dataset in three specific ways:

1. A normalized histogram, which has been optimized with a bin size of 10. This histogram is a first order approximation of the PDF of the RS2 deviations in length from RS2 ship length measurements
2. An optimized gauss kernel density estimation of the PDF [26]. This is a non-parametric fit of the data that approximates the PDF.
3. The measurements of deviations, which are shown along the X axis as small black bars.

[4]Possibly due to the ships detected using RS2 dual-polarization imagery, which provides imagery using two simultaneous radar polarizations.

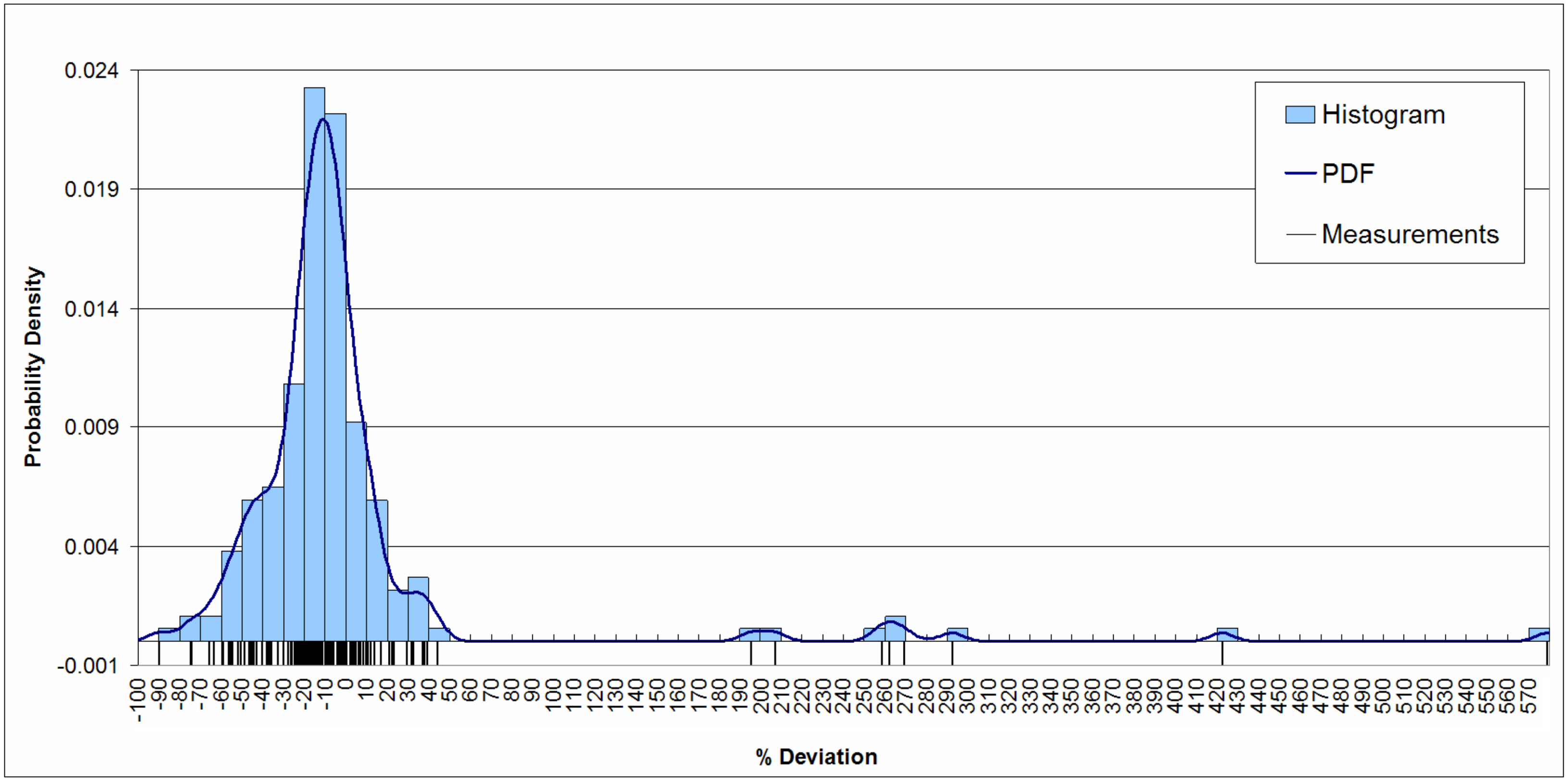


Figure 10: Histogram of relative RS2 length deviations. The lines below the histogram are a one dimensional representation of the raw data points used to generate the histogram.

The characteristics of the data are similar to observations made by other groups analyzing SAR length estimates [20].

The first order approximation of the PDF using a histogram provides a fairly good estimate, however, in terms of modeling the RS2 sensor, one can do better. Shimazaki et al. [26] have developed an optimized kernel density estimation method (sometimes called the Parzen method [27]) to calculate the PDF of stimulated neuron activity. The reason for their innovative method was to optimally map out spikes in the PDF based on only a limited number of sporadic experimental measurements. In their original paper, they compare their kernel density method against several PDF estimation methods, including the histogram method. For smooth (sinusoidal) functions, their kernel method performs with roughly a 50% reduction in the integrated square error compared to the histogram method. Of all the methods they investigated, a method called Bayesian Adaptive Regression Splines (BARS) outperformed their kernel density method for smooth density functions. The BARS method is more sophisticated, and may be useful in future work, however, the kernel method was far simpler and provided good results. The efficiency of the kernel method for estimating PDFs makes it an excellent method to apply to the limited number of measurements from the Operation Driftnet data.

The shape of the distribution shown in Figure 10 is influenced by a number of image quality considerations that affect the accuracy of the length estimation algorithm:

- The effects from using various polarization modes of the SAR sensor creates a multi-modal distribution.
- The effects of incidence angle and ship orientation on the accuracy of the length estimation algorithm could skew the accuracy of the length measurements depending on where in the swath the RS2 contact was detected [6, 28].
- The data was collected over several days in different sea states, which is known to affect the quality of the SAR imagery for ship detection.
- The speed of the vessel will also likely affect reported length, as compared to stationary targets. Length over-estimation may occur due to "smear" resulting from bow waves and wakes. This effect was not investigated in this study, but would be a good area for future investigation.

From an operational (i.e. exploitation) perspective, the details as to why the PDF looks the way it does is not the primary concern, but rather that the knowledge of the PDF shape supports decision making. The model generated from these measurements does not separate all of the influences from polarization modes, sea state, and slew. Instead, it is an averaged model of actual sensor performance across various conditions. This type of sensor model should be considered a partial solution. Further improvements (with more data) could include a multi-situational model that is tailored to the specific conditions of the operation. The trade-off of a multi-situational type statistical model is that complexity is increased, which then increases the time required to make decisions.

It should be noted that the algorithm to estimate ship length will continue to undergo development over time [20]. A simplistic way to keep the model up to date would be to reset and re-generate the sensor model during each operation and to update the model as the operation progresses. This iterative approach would serve to keep the model up to date with current environmental circumstances to ensure that the knowledge about the sensor system remains relevant to the current operation. A more sophisticated way to update the model could involve recursive Bayesian estimation methods [29].

The product of this length analysis is a non-parametric model of the RS2 sensor. The exploitation of the model for decision making is described in section 4.3.

4.2 Analysis of Detected Ship Course

The RS2 data also included information on the possible course of detected ships. However, the accuracy of the course detection algorithm is known to be subject to systematic error [5] so only the alignment of the ships was extracted from the SAR imagery obtained during Operation Driftnet 09. This analysis of the ship courses was performed purely as a sanity check. Given that the direction is expected to be 180 degrees ambiguous, one would expect that half of the detected ships will have the direction wrong (if the algorithm is truly unbiased).

Figure 11 shows a histogram on the absolute error in course between the AIS reported course and the RS2 reported heading. For this figure, there were 185 samples in the dataset. The result is that 49.7% (90) were between -90 and 90 degrees, which is roughly half of the correlations. From this observation, it appears that there is no significant bias in the RS2 course estimation algorithm.

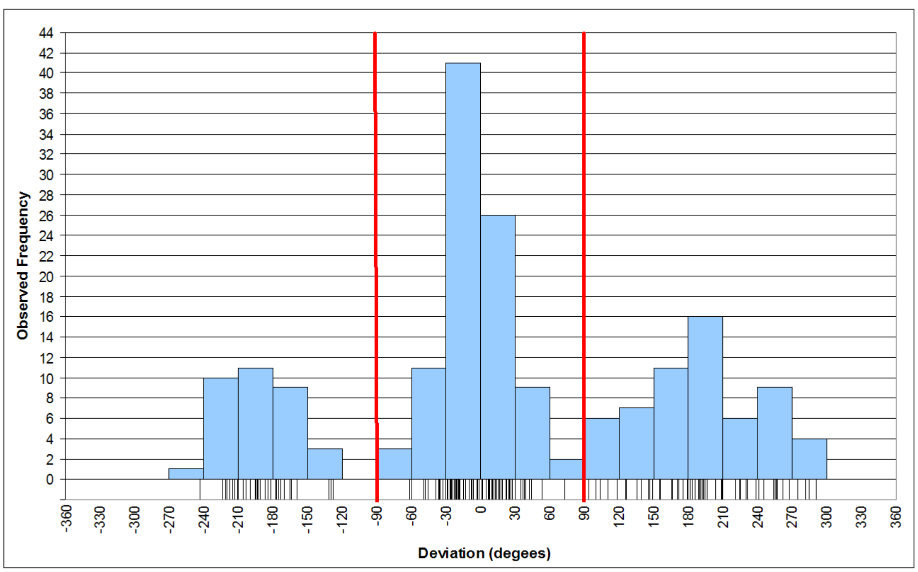


Figure 11: *Histogram of relative RS2 course deviations. The lines below the histogram are a one dimensional representation of the raw data points used to generate the histogram.*

It should be noted, however, that this analysis does have a few limitations.

1. The ships course is not always the same as the heading. Depending on ocean currents and wind, one expects there to be a difference between the course of the ship and the direction the

ship is pointing.

2. The time between the AIS report and the RS2 report is on the order of several hours. Because of this time difference, the ships traveling on great-circle routes may have turned slightly.

3. The directional deviation is likely to be strongly correlated with the speed of the ship, the length of the wake, and weather conditions.

The effect of these limitations is that the spread between the errors on the 0 degrees (correct direction) and +/- 180 degrees (reverse direction) lines would increase. This is what was observed in Figure 11.

This verification of the course algorithm implies that the heading alignment, although not necessarily accurate, can possibly be used to provide amplifying information for sensor correlation. Exploiting this information for sensor correlation has been left for future analysis efforts.

4.3 Decision Aids for Future Operations

Following up on the analysis in 4.1, the results were used to develop decision aids which can be provided to decision makers during operations. Figure 9 provides an empirical estimation using partial data. With the more complete dataset and improved estimation of the PDF in Figure 10, the risk model can be updated. Figure 12 was generated in the same way as Figure 9, which is the result of evaluating Equation 3 targeting a 250 foot long ship:

1. using the empirical data from the first 65 measurements (same as Figure 9),

2. using the empirical data from the 185 detailed measurements, and

3. using the optimized kernel density estimation method.

The general shape of the graph is the same, but the detailed analysis provides a more complete depiction of the risk. The kernel density method provides a result very similar to that observed using the empirical integration method. The main difference is that the kernel method smooths the PDF where there is little measurement data.

During the operation, a 20% risk was decided to be acceptable. This corresponded to a cut-off length of 400 feet using the original dataset. With the revised dataset, the 20% risk line falls to 350 feet, indicating that the original estimation was slightly conservative.

This decision aid can be further expanded by:

- Modifying Equation 3 to target large (commercial) vessels for exclusion. For example, changing the integral in Equation 3 to vary from 250 to infinity to target non-fishing vessels.

- Using different empirical PDFs based on different environmental conditions, or SAR modes.

- Exploring different ways to visualize the risk chart which would make it easier for operators to interpret.

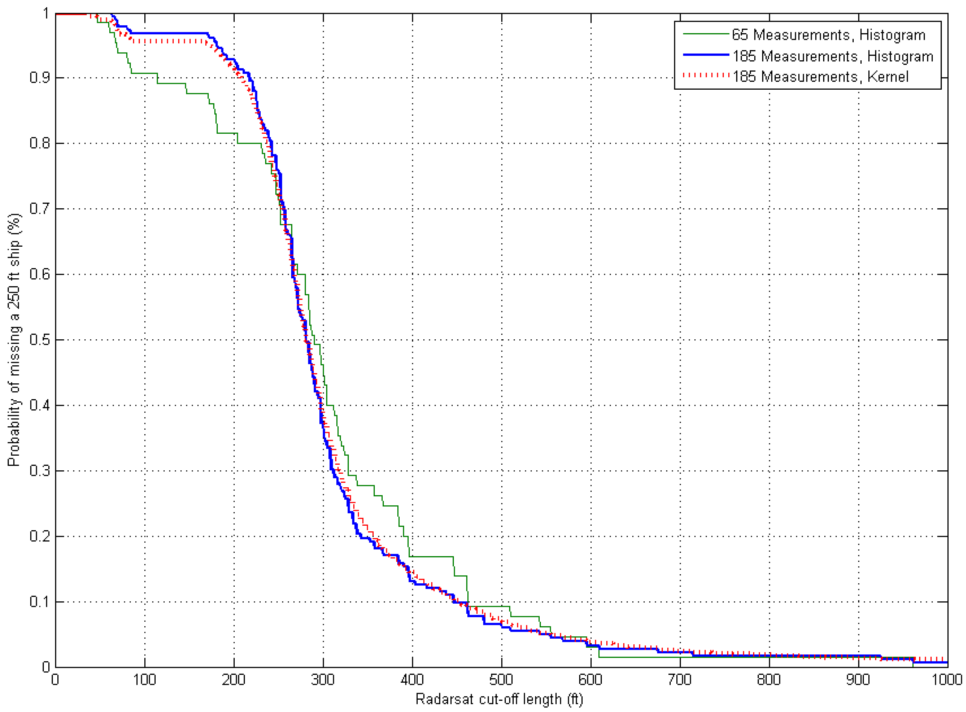


Figure 12: *Risk of missing a 250 foot ship for a given RS2 cut-off length based on measurements of length deviations.*

4.4 Other Potential Applications

In addition to these decision aids based targeting on ship length, targeting based on other attributes may be possible in the future. The ability to measure speed from SAR imagery is a possibility [30–32]. At the moment, this capability is limited to small areas of high resolution imagery, but as algorithms and sensors improve, it is possible that the speed of detected ships could also become available for larger coverage areas. A similar analysis to what was done for ship lengths could be envisaged to generate decision aids to target a subset of slow or fast moving ships.

In addition to decision aids for targeting, statistical sensor models also have the potential to assist automated fusion and classification processes. Using ship length to support classification based on probability density distribution models has been studied elsewhere [33]. When a sensor provides information, and the degree of accuracy of the information is unknown, a statistical model can provide estimates on the error (i.e. reliability) which can then support the decision making within a fusion algorithm [34]. Many fusion algorithms rely on Kalman or particle filtering, which relies on modeling of a system for tracking. With detailed non-parametric models of the behaviour of various sensors, these models can be empirically derived and possibly improve the overall effectiveness of tracking.

5 Future Operational Process

In order to take full advantage of the analysis described in this paper, modifications to the conduct of future remote sensor and flight operations are required. The research undertaken so far can provide enhanced tools and capabilities, but these cannot be properly exploited unless the operational process is tailored to take advantage of them, and integrate them properly into the operational tempo and flow. Enhancing operational processes to take advantage of new tools and capabilities will not simply improve current operational capabilities, it will also add entirely new capabilities that were not previously possible. The work done to support Operation Driftnet 09 identified several areas for future enhancements to operational processes that are described in this section.

5.1 Cued Reconnaissance Process

The process used to conduct this type of operation can be represented as an OODA loop. The “Observe” and “Act” part of this loop is well established, however the “Orient”, “Decide” parts need to be improved. Figure 13 shows the AS-IS, and the COULD-BE processes.

The following operational capabilities could be directly inserted into the loop:

- **Pre-flight Fusion & Analysis**: In the AS-IS model, the data is provided to the operational decision maker in the form of un-fused visualizations using Google Earth. Operational analysis was able to fuse the data from the two sensors and provide to the operational decision maker a more advanced visualization. The ability to fuse, analyze, and visualize the data helped to orient the decision maker before tasking the aircraft.

- **Decision Aids**: The availability of static decision aids to the operators assists in the generation of TOIs.

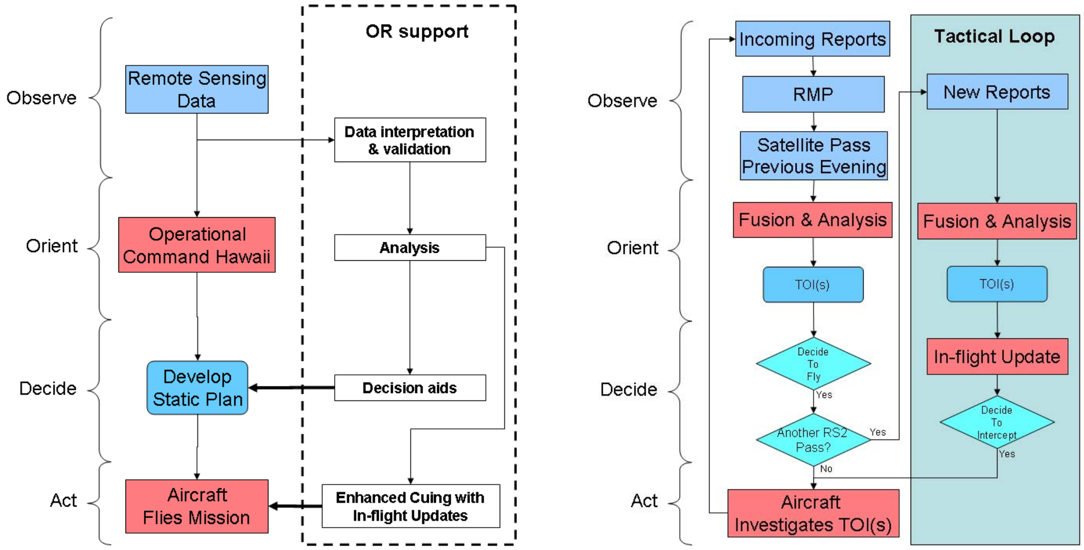
- **Near Real Time (NRT) Fusion & Analysis**: The pre-flight information is used to generate a tasking and forms the basis for conducting a patrol, but as the aircraft is conducting the patrol, new information can become available. The value of the new information degrades over time so the information needs to be analyzed and pushed to the patrolling aircraft as quickly as possible. This NRT analysis can either be done in the operational command and pushed to the aircraft, or the data can be pushed to the aircraft to be analyzed there.

- **In-flight Updates**: The ability to push new information to the aircraft, and simultaneously receive updated information from the aircraft NRT would speed-up the OODA loop.

The following subsections describe how these additional capabilities can be directly incorporated into the OODA loop.

5.2 Pre-flight Analysis Support

The capability to conduct some analysis prior to the flight would improve the “orient” part of the loop. Information is delivered to decision makers, but it’s consumption could be improved.



AS-IS process

COULD-BE Process

Figure 13: *AS-IS and future COULD-BE Operational Processes.*

To improve the consumption of the information, the following capabilities would provide added value:

- Track fusion between sensors improves not just geo-spatial information, but also provides information on which sensors contributed to the track. This information is valuable to assess and characterize the track. For example, a track may be of interest if it was detected with RS2 and not detected by AIS.

- In addition to using the information provided by sensors, information from other sources provides valuable meta-information. The difficulty with exploiting this meta-information is the data fusion required to associate the meta-information to tracks. Automated data fusion capabilities would provide very valuable information before decisions are made.

5.3 Decision Support

The "decide" part of the loop can be improved through knowledge of the sensors and visualization aids.

- Operational decision aids, possibly based on risk or another easy to understand standard, would help to reduce the uncertainty when making decisions. These decision aids would be used by the operational decision maker to help identify TOIs before a flight, and decision aids can also be generated for use by the tactical decision maker (in this case the aircraft operator). A static model for evaluating hard to understand information reduces the cognitive load on the decision maker and therefore reduces the time to execute the decision.

- The decision part of the loop should also include the option to not conduct a patrol. If the "orient" part of the loop does not generate TOIs, and there is a low chance of detecting the type of ship targeted in the mission, then the value of conducting the patrol is decreased. It would be prudent to use all the information available to make a decision that would perhaps push a patrol to another time period or area.

- To further enhance the capability of decision makers, and reduce the time required to make decisions, a target threat analysis tool would be an asset. For example, when looking for ships of certain classification (eg. fishing vessels, merchant of certain size or from certain countries), a tool could be developed to consolidate information from all sensors prior to determining the likelihood that any particular vessel is of interest. Currently, decision makers must combine all the information manually, or consider the various pieces of information separately. This tool would enhance the operators ability to generate TOIs.

5.4 In-flight Updates

Although real-time satellite coverage to support operations is not always available, there is often an opportunity to provide a single pre-scheduled NRT satellite pass. During Operation Driftnet 09, the evening RS2 pass was well aligned with the AIS pass, as can be seen in Figure 6. The information received from the evening RS2 pass also arrives sufficiently early to be processed and fused before the surveillance flight. For these reasons, evening RS2 passes, fused to AIS are useful for pre-flight cuing.

However, the patrols fly during daylight, so morning RS2 passes will have more timely information. Although the information could sometimes be processed before the flight, there were also cases when the download time of the RS2 data did not allow enough time for analysis of the operating area before the flights. When satellite data arrives after the aircraft is already in flight, it would be beneficial to provide the aircraft with this data during the patrol to help direct the remaining flying time. If this occurs, it may be feasible to analyze the previous evenings data and provide information to the aircraft while it transits out for the patrol.

As more data became available, the already airborne CP-140 could be given updates to help reinforce or generate new TOIs. When new data is passed to the CP-140, a new "Tactical" OODA loop is executed to react to the new information.

When the NRT RS2 morning pass is downloaded, it can be passed on to the CP-140 while on patrol. Depending on the download time, this data could be several hours into the flight. The analysis of the morning data can occur either at the operational command and then direction given to the patrol platform, or the raw data could be provided directly to the patrol platform, for them analyze. The result of the new information can generate new TOIs and through the "Tactical" loop, result in redirection of the patrol platform, for example, a redirection to intercept a suspected fishing vessel or group of fishing vessels or a targeting opportunity on a large RS2 contact that did not have AIS.

5.5 In-flight Real-Time Fusion

Once flying, the patrol platforms are closer to employing the information than the operational command. The need to act within a flight means that the “Tactical” OODA loop needs to be completed faster than the operational OODA loop.

Patrol platforms have the potential to use other live data feeds (e.g. aircraft radar or AIS) to make decisions if the operational picture is passed on to the patrols as a stream of in-flight updates; for example:

- Patrol platforms are being equipped with AIS receivers, which would make their RMP more up-to-date information than the RMP in the Operational Centre.
- Patrol platforms can access the NRT RS2 information through in-flight updates.
- Passing the operational RMP in flight to the patrol platform provides assistance for tactical decision making by giving the patrol platform a more complete picture to make decisions.

The ability to correlate the known AIS and RMP targets with the in-flight unidentified NRT RS2 position reports would enhance overall identification levels. This highlights the need for real-time fusion tools directly on-board the patrol platform.

5.6 Patrol Platform Tactical Aids

There are also a few ways in which the “Act” time in OODA loop can be reduced. As the patrol platform is passed TOIs to investigate, the lag between the last known position and the current expected position increases the area that needs to be searched.

To reduce the time required to acquire these TOIs, if the initial time and location of a TOI is known, then a planning tool such as the VOI Reconnaissance Tool (VOIR) [35] can be used in flight to direct the patrol to the TOI. If used in combination with Bayesian searching techniques, VOIR has the potential to improve the effectiveness of patrols. Figure 14 shows a screen shot of VOIR. If RS2 observes a ship in a given location, several hours later, the position of the ship can be predicted given some basic inputs of expected speed and course. For the case of an unknown RS2 contact, the ship has a 180 degree ambiguity in the reported course, and the speed can be estimated using a decision aid.

5.7 Operational Trial of Cuing Process

During Operation Driftnet 09, the operators decided to attempt a conversion of a time late unknown RS2 contact into a TOI and then intercept that target. The actual aircraft tasking and mission report can be found in Annex A and B. Unfortunately, when this procedure was trialled, there was no unknown RS2 contact available. To test of the new operational process, the RS2 reported position of a randomly chosen known contact was passed in-flight to the aircraft, with instructions to intercept and identify. The RS2 contact was 7 hours time-late, with 180 degree course ambiguity (although the course uncertainty could have been resolved when fused with AIS). Using an expanding circle

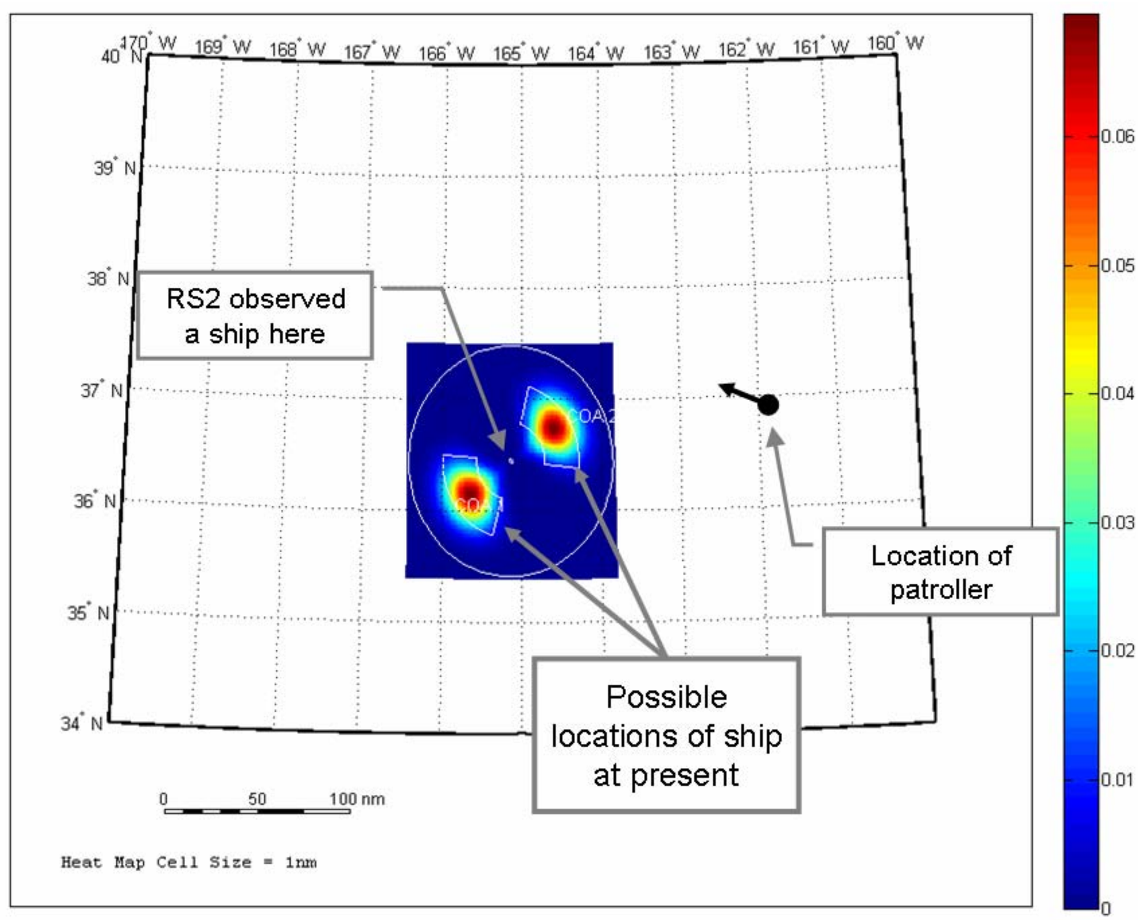


Figure 14: *Mock-up screen shot of the VOI Reconnaissance Tool.*

search area from the previous known position, the aircraft located and intercepted the chosen vessel after a 2-hour search (Annex B. There were other vessels in the area, and since the target vessel was chosen from a list of knowns, the CP-140 did not have a realistic list to compare it against like it would with a true target. The chosen target was 4th vessel found in the search area. If the list of known ships provided to the CP-140 would have excluded the random target, the detection would have been easier given the density of traffic. In the end, the target was visually identified, thereby confirming that the implementation of the process is feasible, however, there is potential to reduce the search time using a tool such as VOIR.

6 Conclusions and Recommendations

The OR support to operations during Operation Driftnet 09 demonstrated the capability to provide near real-time analytical support using RS2 and AIS to ongoing operations. This support enabled the use of RS2 and AIS to cue aircraft patrols, thereby focusing valuable resources on likely TOIs. The initial area of OR support was to investigate the reliability of ship lengths provided by RS2 and to provide a decision aid to operators to allow them to correctly use the RS2 provided length data. OR also provided the capability to obtain enhanced information on AIS hits by creating a tool to query external data sources. The experience gained in this effort also pointed to areas where this support can be operationalized AS-IS to improve surveillance operations, and also pointed to areas where OR support could be further expanded in the future.

6.1 Utility of RS2 for Operations

RS2 provides additional information that is not available from other remote sensors. For example, it is able to actively detect the position and approximate size vessels who are not broadcasting their presence (such as fishing vessels). Two ways that this information can be used are: group detection, which may indicate a fishing fleet; and length information. Approximation of ship lengths using SAR, although not always accurate, does provide additional information to support classification of targets. Combined with appropriate analysis, this information provides useful support to operational decision making.

There is a limit to timeliness for satellite-based capabilities, due to orbit configuration, number of satellites, and ground-satellite communication bottlenecks. These limitations affect persistence and timeliness of information, and need to be addressed. One way is to increase the number of satellites and down-link stations; another way is to improve the processes to speed up the delivery of products to operational users. Planned future enhancements to the RADARSAT constellation can be expected to improve these persistence and timeliness concerns [36]. However, even with one satellite, the Operation Driftnet 09 operation demonstrated that the combination of RS2 and AIS information can be exploited to great advantage.

6.2 Use of RS2 for Cued Reconnaissance

There are still a few barriers to overcome for the use of RS2 for cued reconnaissance during operation Operation Driftnet. The following list presents these barriers, and their proposed solutions.

- The orbit of the RS2 and AIS satellites do not currently line up. This can be addressed either by putting AIS receivers on the RADARSAT satellites [3], or by doing fusion, as was done for this study. Alternatively, one or more AIS micro satellites could be deployed to complement the RS2 orbit [5].

- To use RS2 for cued reconnaissance, one has to able to fuse RS2 reports to other information in order to identify RS2 contacts that are of interest. This capability is something that GCCS

[5] Constellations are currently operational with ORBCOMM and planned by other companies such as ExactEarth

can do manually at present, but automated fusion tools are needed to make this capability practical. With the assistance of fusion tools, this can be done either in the Operational Centre, or on the aircraft.

- If identification is not possible, and only unknown RS2 contacts are available, then the use of decision aids is an option to provide a minimum level of classification to generate TOIs.

6.3 Operation Driftnet 09 Outcomes

During the operational trial of the cuing process described in Section 5.7, the RS2 position of a randomly chosen known contact was passed in-flight to the aircraft, with instructions to intercept and identify. The CP-140 visually identified the contact, thereby confirming that the implementation of the process is feasible. Given the time it took to search the area, and the RS2 cuing information, the VOIR tool could have helped to make the search more efficient.

6.4 Recommendations for Future Work

During the discussions in this paper, several areas of future work were identified.

- A study to compare the cuing ability of RS2 versus, or in combination with other sensors should be undertaken.
- An analysis to identify an ideal sensor mix to generate the RMP for this specific type of operation would be beneficial.
- Further development and improvement of operational procedures is required. This activity should not be driven bottom-up (based on capability), but top down (based on desired effect).
- The past and current use of the CP-140 has been mainly to conduct wide-area surveillance. The impact on training and operations moving to more cued reconnaissance roles needs to be investigated.
- Ongoing research into improving the empirical models used in the decision aids should be conducted. As more data is collected to build the models, more variables can be considered in the models. The effects of various operational conditions (such as weather, incidence angle, and geographic location) can be included to further refine the model.
- Any decision aids developed will have a certain "shelf life". Depending on the decision aid and the application, the information may need to be updated daily, weekly, or quarterly. A simple way to generate decision aids should be investigated.
- The OR analysis tools used for this work are still at a low Technology Readiness Level (TRL). Further improvements to Prototype RAT and the development of new capabilities within the tool set is are recommended.
- Generating these sensor models can be useful for more than just characterization of the sensors. Deficiencies and areas for improvement can be identified which would drive the development of the next generation of sensors and systems.

- The correlation algorithms used were very labour intensive. Further development of the algorithms, and their automation is required.
- Track fusion algorithms may be able to take advantage of the empirical sensor models described in this paper. The possibility of integrating the sensor models into fusion algorithms, and feedback track fusion results to improve the models should be investigated.
- To progress the development of the cued operational process, it is recommended that OR be involved and provide support during future Operation Driftnet operations.

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Annex A: Sample Tasking to CP140

DRIFTNET PATROL TASKING / DAILY SPINS FOR 17 SEP 09

ATO MISSN ID P26001 DEMON15 19 Z A/B

1. PATROL AIM.

PRIMARY AIM IS TO ATTEMPT TO UTILIZE THE AIRCRAFT TO LOCATE AND COLLECT VISUAL DATA FROM A TARGET OF INTEREST GENERATED BY RS2. COLLECT MAX SURV DATA OF OTHER CNTCS FROM HIGH LEVEL WHILE IN TRANSIT / OVERFLIGHT. SHOULD AN IUU VSSL BE DETECTED ENROUTE IT WILL BECOME THE PRIORITY.

2. PLANNING FACTORS.

MISSION SHALL BE PLANNED FOR PLE AND MAX ONSTA DAYLIGHT. DUE REGARD IS AUTHORIZED AS REQD IN ALTREV AND OTHER OCEANIC AIRSPACE.

3. INTEL.

AREAS OF INTEREST (AOI): AREA 1 BASED ON RS 2 PASS AT 1653Z

4. MISSION EXECUTION. CONDUCT MISSION IAW HSDN STANDING SPINS. NOTE:

A. TRANSIT DIRECT TOWARD POSITION 38N-162W. ANTICIPATE RECEIVING SATCOM CALL WITH NOTIFICATION OF RS 2 DATA AT APPROX 2200Z. RS2 DATA WILL BE UPLOADED INTO DRIFTNET 2009 FOLDER ON FTP SITE. EXPECT TO BE TARGETED FOR A TIME LATE SEARCH FOR A RS2 TARGET OF INTEREST (LENGTH ESTIMATE LESS THAN 400 FEET). SHOULD THERE BE NO RS2 TARGET MEETING THIS CRITERION, ANOTHER CONTACT WILL BE SELECTED FOR THE SEARCH. THE MISSION WILL CONCLUDE AND RTB ONCE A HIGH CONFIDENCE CONVERSION FROM RS2 TO VISUAL HAS TAKEN PLACE AND FULL DATA COLLECTION HAS OCCURED. AT THAT POINT MAKE CONTACT WITH RACE P HONOLULU ON BB. DURING THE PREVIOUS CORROBRATION MISSION IN AREA 1 MOST RS 2 TARGETS WERE DETERMINED TO BE HDG EAST SO ENSURE THAT SUFFICIENT SEARCH EXPANSION IS PROVIDED TO THE EAST. AN AREA EXTENSION OF 200NM TO THE EAST IS AUTHORIZED BUT NO ALTREV EXTENSION HAS BEEN SET UP.

B. ON THE OFF CHANCE THAT TIME WILL PERMIT USCG D14 HAS REQ SURV OF AN AREA TO THE WEST BOUNDED BY 30N TO 34N AND 178E TO 172W. THIS IS AN AREA THAT D14 HAS HAD SOME HISTORIC INTEREST IN DUE TO PREVIOUS FISHERY VIOLATIONS AND IT HAS NOT BEEN PATROLLED IN A WHILE. UNFORTUNATELY RS2 DATA WAS NOT AVAIL FOR THIS AREA 17 SEP. AREA EXTENSION IS GRANTED SHOULD THE NEED ARISE BUT NOT ALTREV EXTENSION HAS BEEN ARRANGED. LOCAL NOAA AGENT TOMMY FRIEL COULD BE CONSULTED FOR THE HISTORY/LOCAL KNOWLEDGE OF THOSE WATERS IF NEEDED 808-330-3768.

C. IF DATA COLLECTION ON AN IUU/HSDN VSL SOMEHOW BECOMES RESTRICTED (IE FUEL / WX), REFER TO EXPERTISE OF DFO / NMFS AGENT TO FURTHER REFINE DATA PRIORITIES LISTED IN SPINS PARA E 6.

D. ONSTA/OFFSTA SURV STARTS AND ENDS AT HSDN OPAREA BOUNDARY.

E. PROVIDE QUANTITATIVE (IE NUMBER OF VESSELS) AND QUALITIVE DETAILS (100 PCT COVERAGE) FOR EACH PATROL SUB-AREA SURVEYED. PARTIAL COVERAGE IS BEST EXPLAINED IN TERMS LIKE QUOTE 4B 70 % COVERED NORTH OF 42N AND WEST OF 165E; 16 VESSELS DETECTED ON RDR PLUS 3 VISID UNQUOTE.

5. 48 HR FORECAST - 18/19SEP - RTB COMOX; DATE DEPENDANT ON SQN REQRS FOR AIRCRAFT RETURN FOR MISSIONS.

Annex B: Mission Report from Operational Process Trial

EVENT P26001 WAS TASKED TO ATTEMPT A CONVERSION OF A TIME LATE RS2 CNTC INTO A VIS ID. IT WAS HOPED THAT RS2 WOULD DETECT A VOI IE CNTC LESS THAN 250FT THAT COULD BE PROVIDED TO THE AIRCRAFT FOR TARGETTED SURV. AN ANTICIPATED AREA OF OPERATIONS WAS BRIEFED TO THE CREW BEFORE TAKE-OFF AND WAS TO BE REFINED VIA AN FTP UPDATE ENROUTE. P26001 TOOK OFF FROM KANEOHE BAY AT 1908Z FOR HSDN OP AREAS 1B-1D EXPECTING RECEIPT OF RS 2 DATA BY 2200Z. P26001 ARRIVED ONSTA IN SOUTH AT 2105Z AND CONTINUED NORTH TOWARDS AN ANTICIPATED AREA OF OPERATIONS. UNFORTUNATELY THE 2200Z RS2 DATA WAS DELAYED FOR UNKNOWN REASONS AND AT 2244Z RACE(P) HAWAII DIRECTED P26001 TO PATROL AN EASTERN AREA BOUNDED BY 38N-41N AND 160W-15530W WHILE AWAITING THE DATA. 100 PERCENT OF THAT AREA WAS COVERED WITH NO VOI DETECTED. BY 2340Z RACE(P) HAD RECIEVED THE RS2 DATA AND TASKED P26001 VIA SATPHONE TO LOCATE AND IMAGE A RS2 CONTACT THAT WOULD ACT A SIMULATED VOI AS THE RS2 SWATH DID NOT DETECT ANY CONTACTS LESS THAN 250 FT. EVENT PROCEEDED 400NM TO SW TO THE LKP OF A 1700Z RS2 FIX OF A 600 FT VESSEL AT 4000N-16515W, VESSEL COURSE 250T WITH 180 DEGREE AMBIGUITY. UPON ARRIVAL AT LKP, DATA WAS MORE THAN 7HRS TIME LATE SO EVENT ESTABLISHED A SEARCH AREA OF 150 NM RADIUS ON DATUM WITH A 20KTS EXPANDING CIRCLE. AN APPROPRIATE RADAR DETECTION RANGE WAS USED TO SEARCH FOR THE 600FT VOI. P26001 LOCATED 4 CONTACTS WITHIN THE SEARCH AREA OF THE VOI. WHILE CONDUCTING A HOMING TO THE LAST CONTACT AND DEEMED MOST LIKELY TO BE THE RS2 SIM VOI, P26001 RECEIVED ADDITIONAL AIS INFO FROM RACE(P) HAWAII THAT FULLY CORROBORATED THIS CONTACT AS THE RS2 SIM VOI. VISUAL ID AND DATA COLLECTION WAS CONDUCTED ON THE SIM VOI. DURING THE ONSTA PERIOD P26001 LOCATED 5 MERCHANT, 2 NAVAL, 1 FISHING, AND 2 UNKNOWN CONTACTS WITHIN THE SEARCH AREAS ASSIGNED. ALL CONTACTS WERE AIR REPORTED VIA THE FTP WEBSITE. IMAGERY OF THE SIM VOI WAS ALSO TRANSFERED TO THE FTP WEBSITE. EVENT DID NOT HAVE ENOUGH FUEL FOR D14 ADDITIONAL TASK FOR SURV TO THE WEST, SOUTH OF AREAS 3-4 D. OFFSTA AT 0235Z AND RTB KANEOHE BAY AT 0425Z.

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Annex C: Lloyd’s Database Query Script

To query Lloyd’s database, a Visual Basic for Applications (VBA) script was created. Figure C.1 shows the main page of the workbook.

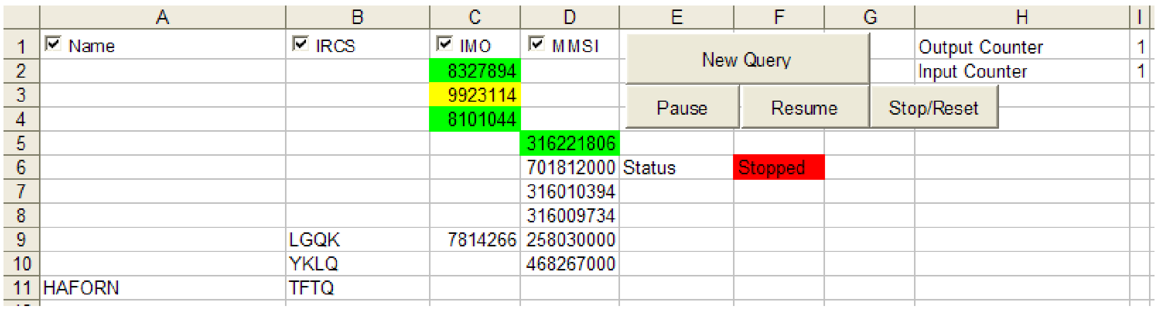

Figure C.1: *Screenshot of the Lloyd’s database query interface.*

When the user presses the “New Query” button, the following code is executed:

```
Dim Browser As Object
Dim Status As String

Private Sub QueryButton_Click()

'URL Information
LLOYDSURL = "http://lloyds.canmarnet.gc.ca"
IRCSQueryStringA =
    "http://lloyds.canmarnet.gc.ca/authenticated/res_ships.aspx?Page=1&Type=CallSign&SubType=starts&SearchString="
IRCSQueryStringB = "&Records=25&Order=VesselName"
NAMEQueryStringA =
    "http://lloyds.canmarnet.gc.ca/authenticated/res_ships.aspx?Page=1&Type=VesselName&SubType=starts&SearchString="
NAMEQueryStringB = "&Records=25&Order=VesselName"
MMSIQueryStringA =
    "http://lloyds.canmarnet.gc.ca/authenticated/res_ships.aspx?Page=1&Type=MMSI&SubType=starts&SearchString="
MMSIQueryStringB = "&Records=25&Order=VesselName"
IMOQueryStringA = "http://lloyds.canmarnet.gc.ca/authenticated/res_ships.aspx?Page=1&Type=LRNO&SubType=&SearchString="
IMOQueryStringB = "&Records=25&Order=VesselName"

Call InitializeBrowser

'Create Output Headers
Call CreateHeaders

'Set InputCounter to 1
Sheet1.Cells(2, 9) = 1

'Set status to Running
Status = "Running"
Sheet1.Cells(6, 6) = Status

Sheet1.Range("A:D").Interior.ColorIndex = xlColorIndexNone

While Status <> "Stopped"
    If Status <> "Paused" Then
        'Scan the input line
        InputC = Sheet1.Cells(2, 9) 'Input Counter
        OutputC = Sheet1.Cells(1, 9) 'Output Counter

        'Check for Finishing Condition
        MoreData = 0
        If Sheet1.Cells(InputC + 1, 1) <> "" Then
            MoreData = 1
        End If
        If Sheet1.Cells(InputC + 1, 2) <> "" Then
            MoreData = 1
        End If
        If Sheet1.Cells(InputC + 1, 3) <> "" Then
            MoreData = 1
        End If
        If Sheet1.Cells(InputC + 1, 4) <> "" Then
            MoreData = 1
```

```
End If
If MoreData = 0 Then
    Status = "Stopped" 'The line contains no data -> Stop
End If

'Check to see if there are any fields checked off
If Sheet1.Cells(1, 10) = False And Sheet1.Cells(2, 10) = False And Sheet1.Cells(4, 10) = False And
     Sheet1.Cells(5, 10) = False Then
    'User did not choose any fields to search by
    Status = "Stopped"
End If

'If we are still good, then continue...
If Status <> "Stopped" Then
    'Start by searching by IMO, then MMSI, then IRCS, then Name
    'Search by IMO:
    ShipFound = 0
    If Sheet1.Cells(4, 10) = True And ShipFound <> 1 Then
        IMO = Sheet1.Cells(InputC + 1, 3)
        If IMO <> "" Then
            R = QueryLLOYDS(IMOQueryStringA, IMOQueryStringB, IMO)
            If R = 1 Then
                Sheet1.Cells(InputC + 1, 3).Interior.Color = RGB(0, 200, 0)
                ShipFound = 1
            Else
                Sheet1.Cells(InputC + 1, 3).Interior.Color = RGB(255, 255, 0)
                OutputC = OutputC + 1 'Increment the output counter
                Sheet1.Cells(1, 9) = OutputC 'Save to Excel Page
                Sheet2.Cells(OutputC, 1) = "UNKNOWN IMO " + Str(IMO)
                Sheet2.Cells(OutputC, 5) = IMO
            End If
        End If
    End If
    If Sheet1.Cells(5, 10) = True And ShipFound <> 1 Then
        MMSI = Sheet1.Cells(InputC + 1, 4)
        If MMSI <> "" Then
            R = QueryLLOYDS(MMSIQueryStringA, MMSIQueryStringB, MMSI)
            If R = 1 Then
                Sheet1.Cells(InputC + 1, 4).Interior.Color = RGB(0, 200, 0)
                ShipFound = 1
            Else
                Sheet1.Cells(InputC + 1, 4).Interior.Color = RGB(255, 255, 0)
                OutputC = OutputC + 1 'Increment the output counter
                Sheet1.Cells(1, 9) = OutputC 'Save to Excel Page
                Sheet2.Cells(OutputC, 1) = "UNKNOWN MMSI " + Str(MMSI)
                Sheet2.Cells(OutputC, 5) = MMSI
            End If
        End If
    End If
    If Sheet1.Cells(2, 10) = True And ShipFound <> 1 Then
        IRCS = Sheet1.Cells(InputC + 1, 2)
        If IRCS <> "" Then
            R = QueryLLOYDS(IRCSQueryStringA, IRCSQueryStringB, IRCS)
            If R = 1 Then
                Sheet1.Cells(InputC + 1, 2).Interior.Color = RGB(0, 200, 0)
                ShipFound = 1
            Else
                Sheet1.Cells(InputC + 1, 2).Interior.Color = RGB(255, 255, 0)
                OutputC = OutputC + 1 'Increment the output counter
                Sheet1.Cells(1, 9) = OutputC 'Save to Excel Page
                Sheet2.Cells(OutputC, 1) = "UNKNOWN IRCS " + IRCS
                Sheet2.Cells(OutputC, 2) = IRCS
            End If
        End If
    End If
    If Sheet1.Cells(1, 10) = True And ShipFound <> 1 Then
        Name = Sheet1.Cells(InputC + 1, 1)
        If Name <> "" Then
            If InStr(1, Name, "UNKNOWN", vbTextCompare) Then
                'Do nothing
            Else
                R = QueryLLOYDS(NAMEQueryStringA, NAMEQueryStringB, Name)
                If R = 1 Then
                    Sheet1.Cells(InputC + 1, 1).Interior.Color = RGB(0, 200, 0)
                    ShipFound = 1
                Else
                    Sheet1.Cells(InputC + 1, 1).Interior.Color = RGB(255, 255, 0)
                    OutputC = OutputC + 1 'Increment the output counter
                    Sheet1.Cells(1, 9) = OutputC 'Save to Excel Page
                    Sheet2.Cells(OutputC, 1) = Name
                End If
            End If
        End If
    End If
    'Increment Input Counter
    InputC = InputC + 1
    Sheet1.Cells(2, 9) = InputC
```

```
            'Sheet1.Cells(InputC + 1, 1).BorderAround = 1
            'Sheet1.Cells(InputC + 1, 1).Interior.Color = RGB(0, 200, 0)
            'Sheet1.Cells(InputC, 1).Interior.Color = RGB(255, 255, 255)
        Else
            'Sheet1.Cells(InputC + 1, 1).Interior.Color = RGB(255, 255, 255)
        End If
    End If
    DoEvents    'Keep Excel responsive
Wend
Browser.Visible = True 'Make browser visible

End Sub


Private Function ParseQuery()
LLOYDSURL = "http://lloyds.canmarnet.gc.ca"

'URLS for any Matches
Dim URLS(1 To 20) As String

'Get the line we are at on the ouput page
OutputC = Sheet1.Cells(1, 9) 'Output Counter

'Get all the hits
Set o = Browser.Document.All.tags("A")
L = o.Length 'Number of <A></A> Tags
'Search for the string ovw_ship.aspx
NumberOfHits = 0
For H = 0 To L - 1
  If InStr(1, o.Item(H).outerhtml, "ovw_ship.aspx", vbTextCompare) Then
    NumberOfHits = NumberOfHits + 1
    URLS(NumberOfHits) = o.Item(H).outerhtml
  End If
Next
If NumberOfHits > 0 Then
    For H = 1 To NumberOfHits
        OutputC = OutputC + 1 'Increment the output counter
        Sheet1.Cells(1, 9) = OutputC 'Save to Excel Page

        g = URLS(H)
        c1 = InStr(1, g, """", vbTextCompare)
        c2 = InStr(c1 + 1, g, """", vbTextCompare)
        DetailURL = LLOYDSURL + Mid(g, c1 + 1, c2 - c1 - 1)
        DetailURL = Replace(DetailURL, "amp;", "")

        OpenPage (DetailURL) 'Open the webpage

        'Get all the <SPAN></SPAN> Tags
        Set t = Browser.Document.All.tags("SPAN")
        For K = 0 To t.Length - 1
            If InStr(1, t.Item(K).outerhtml, "_ctl0_VesselName", vbTextCompare) Then
                Sheet2.Cells(OutputC, 1) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl0_CallSign", vbTextCompare) Then
                Sheet2.Cells(OutputC, 2) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl0_Flag", vbTextCompare) Then
                Sheet2.Cells(OutputC, 3) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl0_LRNumber", vbTextCompare) Then
                Sheet2.Cells(OutputC, 4) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl0_MMSI", vbTextCompare) Then
                Sheet2.Cells(OutputC, 5) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl0_ShipType", vbTextCompare) Then
                Sheet2.Cells(OutputC, 6) = t.Item(K).innerhtml
            End If
            If InStr(1, t.Item(K).outerhtml, "_ctl1_LOA", vbTextCompare) Then
                Sheet2.Cells(OutputC, 7) = t.Item(K).innerhtml
            End If
        Next
    Next
    'Indicate that the search produced results
    ParseQuery = 1
Else
    'No Hits
    ParseQuery = 0
    'No matches
End If

End Function
Private Sub OpenPage(ByVal URL As String)
Browser.navigate (URL)
    While Browser.busy: DoEvents: Wend 'Wait for page to load
    Do Until Browser.readystate = 4: DoEvents: Loop 'Wait until Browser has parsed the webpage
End Sub
```

```
Private Function QueryLLOYDS(ByVal QA As String, ByVal QB As String, ByVal Q As String)
'Function to query LLOYDS

If Q <> "" Then
    'Only Query Something Provided
    QueryString = QA + Q + QB

    'Execute Query
    OpenPage (QueryString)
    QueryLLOYDS = ParseQuery()
End If
End Function
Private Sub InitializeBrowser()
Set Browser = CreateObject("InternetExplorer.Application")
Browser.Visible = False 'Make browser visible
End Sub
Private Sub CreateHeaders()
i = 1
Sheet2.Cells(i, 1) = "Name"
Sheet2.Cells(i, 2) = "IRCS"
Sheet2.Cells(i, 3) = "Flag"
Sheet2.Cells(i, 4) = "IMO"
Sheet2.Cells(i, 5) = "MMSI"
Sheet2.Cells(i, 6) = "CLASS"
Sheet2.Cells(i, 7) = "LENGTH"

End Sub
```

List of abbreviations

ACE Attribute Correction Engine

AIS Automatic Identification System

AOR Area of Responsibility

ART Additional Reference Table

ASAR Advanced SAR

BARS Bayesian Adaptive Regression Splines

C2 Command and Control

CCG Canadian Coast Guard

CF Canadian Forces

CORA Centre for Operational Research and Analysis

DFO Department of Fisheries and Oceans

DRDC Defence Research and Development Canada

ELINT Electronic Intelligence

GCCS Global Command and Control System

GPS Global Positioning System

IMO International Maritime Organization

JTFA Joint Task Force (Atlantic)

JTFP Joint Task Force (Pacific)

LRPA Long Range Patrol Aircraft

MMSI Maritime Mobile Service Identity

MUSIC Multi Sensor Integration in a Common Operating Environment

NMFS National Marine Fisheries Service

NRT Near Real Time

NTS Nanosatellite Tracking of Ships

OGD Other Government Department

OODA Observe Orient Decide Act

OR	Operational Research
ORT	Operational Research Team
OTG	Over The Horizon (OTH) Targeting GOLD (OTH-T-GOLD)
PDF	Probability Density Function
Prototype RAT	Prototype RMP Analysis Toolset
RMP	Recognized Maritime Picture
RS1	RADARSAT-1
RS2	RADARSAT-2
SA	Situational Awareness
SAR	Synthetic Aperture Radar
SOP	Standard Operating Procedure
SQL	Structured Query Language
TOI	Target of Interest
TRL	Technology Readiness Level
UN	United Nations
USCG	United States Coast Guard
VBA	Visual Basic for Applications
VOIR	VOI Reconnaissance Tool

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